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A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
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Journal of Sedimentary Petrology

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 6, NO. 2, PP. 55–84, FIG. 1, TABLES 1–13,
AUGUST, 1936

HEAVY MINERALS OF THE ST. PETER SANDSTONE IN WISCONSIN

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ABSTRACT

The heavy mineral suite of the St. Peter sandstone is rather uniform over large areas, but there is a pronounced concentration of leucoxene and ilmenite in south-central Wisconsin. Zircon, tourmaline, leucoxene, and ilmenite compose about 97 per cent of the heavy minerals, with anatase, ceylonite, apatite, rutile, staurolite, and garnet constituting the other 3 per cent. Pyrite, celestite, jarosite, and dahllite are present in minor quantities, but in some cases they flood the sample.

The heavy mineral inclusions within the quartz grains were recovered by means of a new procedure and were found to be different from those associated with the quartz grains and to consist of zircon, apatite, biotite, hornblende, titanite, rutile, ilmenite, garnet, pyrite, tourmaline, fluorite, kyanite, and leucoxene.

The quartz grains, classified on the basis of inclusions as suggested by Mackie, indicate that the ultimate source of the sands of the St. Peter was largely a granitic terrane. The immediate source seems to have been a sedimentary terrane.

INTRODUCTION

Statement of Problem.—A study of the heavy minerals of the St. Peter sandstone in Wisconsin was undertaken: (1) in order to obtain information concerning the suite of minerals present, (2) to determine their variations regionally and stratigraphically, (3) to determine the value of heavy minerals as a basis for differentiating the St. Peter from the Upper Cambrian sandstones. It was also expected that the heavy minerals might give some information concerning the distributive province from which the sands were derived, and thus some hint as to the paleogeography of the time of deposition.

Acknowledgments.—The writer wishes to express his thanks to Dr. W. H. Twenhofel under whose direction the research was carried on, to Mr. F. T. Thwaites, Mr. E. R. Shorey and other members of the University of Wisconsin faculty who have assisted.

Description of the St. Peter Sandstone in Wisconsin.—The Ordovician succession of Wisconsin consists from the base upward of the following units: Oneota-Shakopee dolomite, St. Peter sandstone, Platteville dolomite and limestone, Decorah shale and limestone, Galena dolomite and Maquoketa shale. The St. Peter sandstone lies disconformably above the Oneota-Shakopee dolomite and apparently conformably below the Platteville limestone.

The St. Peter sandstone outcrops in a U-shaped band on the flanks of the Wisconsin Arch with the base of the U across the southern part of the state and the uprights on either side. On the east the formation may be traced practically to the Michigan line where it disappears beneath the drift. It has not been recognized in

northern Michigan (1). On the west flank of the Wisconsin Arch the sandstone is much dissected and forms a belt of outliers which extends as far north as Hudson, Wisconsin. The thickness of the St. Peter sandstone in Wisconsin ranges from a single layer of sand grains to well over three hundred feet. The pre-St. Peter erosion surface with a maximum relief of three hundred feet or more is cut deeply into the underlying rocks, and locally the St. Peter rests on various Cambrian beds. Thwaites (2) states that, "Over an area of several thousand square miles in eastern Wisconsin and in portions of northern Illinois, the St. Peter rests upon the Cambrian; formations ranging from Jordan to Eau Claire have been distinguished at different places as underlying the St. Peter."

The lower part of the St. Peter is composed of yellow to red, fine-grained sandstones with interbedded red and green shales. The basal strata consist of a few feet of unstratified red to green clays in which are angular chert fragments.

The upper part of the St. Peter is composed of massive, poorly-bedded, white to yellow or yellowish-brown, fine- to medium-grained friable sandstone. Rounding, frosting and pitting appear to be largely confined to the coarser grains. Sorting is very good, although occasional beds may be found in which the material ranges from coarse sand to fine silt. Some of the beds of the St. Peter are locally quartzitic, but, in general, the sandstone is so poorly cemented that the rock may be quarried for sand. Long and moderately steep cross-laminae, which dip in more or less the same direction over fairly large areas, appear to be more characteristic of the St. Peter in Wisconsin, than is the development of horizontal bedding.

Wedge-shaped cross-laminated units are present about twenty feet below the base of the Platteville on the north side of Blue Mound. This type of cross lamination, which appears to be rare in the St. Peter sandstone, is said to occur in wind deposited sands (3).

Ripple marks appear to be very uncommon in the St. Peter sandstone of Wisconsin. They have been described by Strong (4) at one location, as being, "very regular, parallel and well defined," but no mention is made whether they are of the current or oscillation type.

In central and western Wisconsin the St. Peter sandstone is generally overlain by greenish-blue shales, and greensands, which range in thickness from a few inches to a few feet. This horizon has been named the Glenwood formation by Calvin (5). In Wisconsin the shales are rather arenaceous. The sands consist of two general sizes; fine-grained, angular, unfrosted grains and medium to coarse, well-rounded and frosted grains. The green color is due to glauconite in the form of dust-like particles. The greensands often grade laterally into yellowish-brown sandstone, the color of which is chiefly due to the presence of limonite and jarosite. Limonitic concretions, which often contain marcasite or pyrite in their centers, are not uncommon at

this horizon. Bedding, and particularly cross-bedding, is usually much better developed in the Glenwood beds than in the St. Peter sandstone.

Theories as to the Manner of Deposition.—The manner in which the St. Peter sandstone was deposited has been a debatable subject for years. Two general theories have been advanced: one considering the St. Peter, an eolian deposit, and the other ascribing the deposition to marine sedimentation.

Berkey (6) concluded that large quantities of sand were spread by a retreating sea over a rather uniform plain. Winds then shifted these sands extensively and produced the purity and textural characters of the formation. A readvance of the sea completed the assorting of the sands and introduced marine fossils.

Grabau (7) considered the St. Peter a dune deposit, subsequently partially reworked by a transgressing sea. The fineness and uniformity of grain, absence of stratification and splitting into vertical slabs were cited as evidence of wind deposition.

Trowbridge (8) and Dake (9) considered that, in general, the St. Peter sands were transported by rivers and deposited in shallow marine waters. The similarity of the St. Peter, as to purity, size and uniformity of grain, degree of rounding and frosting, to known marine Cambrian formations is pointed out. The lack of wind polishing and facetting on the chert pebbles in the basal conglomerate, and the general absence of dune structures are brought forward as evidence that the St. Peter is not primarily an eolian deposit. As evidence of aqueous origin, Dake has cited oscillation ripple marks found near the base of the formation, limestone layers extending from the south to as far north as Illinois and Iowa, and the better development of bedding than cross-bedding. (This last observation does not apply very well to the St. Peter in Wisconsin.)

The chief evidence for a marine origin of the St. Peter sandstone is the presence of fossils found in the formation at St. Paul, in Wisconsin and possibly at Kentland, Indiana. Sardeson (10) collected pelecypods, gastropods, cephalopods, brachiopods, bryozoans and sponges from several horizons more than sixty feet below the top of the formation at St. Paul, Minnesota. He also reports fossils from the top of the St. Peter (possibly the Glenwood horizon) at Dodgeville, Wisconsin. Fossils have also been found in sandstone considered to be St. Peter, at Kentland, Indiana (11). A marine origin can be postulated only for those parts of the formation in which the marine fossils were found.

The irregular surface upon which the St. Peter was deposited and the unsorted character of the basal part of the formation are cited as evidence by Twenhofel and Thwaites against marine deposition (12).

The manner in which the St. Peter sandstone was deposited is still an open question; at some localities it seems to be marine, whereas at others it has eolian aspects. It is evident, however, that at most places in Wisconsin it is a shallow-water deposit

which is not necessarily marine.

Previous Work on the Heavy Minerals.—The heavy minerals of the St. Peter sandstone have been studied by Cordry (13) and Edson (14) in Missouri, by Giles (15) and Edson (14) in Arkansas, by Lamar (16) in Illinois, by Wanenmacher (17) and Thiel (18) in Wisconsin, by Shrock and Malott (11) in Indiana, by Edson (14) and Thiel (18) in Minnesota, and by Edson (19) in Kansas.

Lamar and more recently Thiel made use of the jig table to effect a preliminary separation of quartz from the heavy minerals. This is unfortunate as the introduction of a sizing and rolling factor by the jig table affects the relative heavy mineral percentages, and thus makes comparison of the relative percentages obtained in this manner with those from a complete heavy liquid separation useless. The use of the jig table for a preliminary separation of the heavy minerals from the light minerals is not necessary and the procedure should be abandoned when relative percentage frequency results are sought.

PROCEDURE

Sampling.—Most of the samples were obtained from outcrops by cutting a channel two inches wide across the beds so as to include two feet of the formation in each sample. The samples averaged about five pounds in weight.

Well cuttings of the St. Peter were studied in order to determine the heavy mineral content where the formation is not exposed at the surface. Contamination is here a factor as sand or other material from another horizon in the same formation or higher formations may be introduced. Assuming that the heavy mineral suite is the same throughout a formation, introduction of material from another horizon in the same formation is very difficult to detect as the introduced minerals are the same as the minerals present. In this case there may be a large error in the percentage of each mineral constituent. In the second case contamination may be more easily detected, particularly if the formations above do not contain the same heavy minerals. Several sections of well cuttings had to be abandoned, because the samples were very evidently contaminated. Fragments of igneous rocks up to one-eighth inch in diameter, as well as fresh, angular grains of hornblende, pyroxene, epidote, etc., were found. The well samples studied, taken at five foot intervals, represent the Milwaukee, Franksville, Oconomowoc, Depere, Cedarburg and Two Rivers sections.

Laboratory Technique.—Most of the samples were poorly cemented, but in order to completely free the grains the following procedure was carried out. The sample was first passed through a jaw crusher in order to break up the larger pieces, and then through a set of rolls, with the rolls so adjusted that a minimum number of grains was crushed. After passing the rolls the sample was screened through an 80-mesh sieve. The material passing through the sieve consisted essentially of indi-

vidual grains, whereas the material caught on the sieve was mostly cemented grain clusters. The grain clusters were then passed through a disk crusher, with the disks so adjusted that the grains would be broken apart, but not crushed. Both fractions were then combined to produce a sample in which most of the individual grains were free.

In some cases it was necessary to treat the sample with hot, dilute hydrochloric acid in order to remove the coating of iron oxide on the grains. Pyrite and marcasite, flood minerals in a few cases, were removed by treating the samples with hot nitric acid after a preliminary separation indicated other soluble minerals to be absent.

Samples containing clay or other very fine material were washed by decantation. The heavy mineral separation was carried out with tetrabromoethane (Sp. gr. 2.96) using the procedure described by Reed (20). Acetone was used to wash the grains free of the tetrabromoethane, and the heavy liquid was recovered by means of the well known water recovery method (21).

Both jarosite and feldspar were separated from the samples by centrifuging.

THE MINERALS OF THE ST. PETER SANDSTONE

Light Minerals.—The light minerals (specific gravity less than 2.96) present in the St. Peter sandstone are quartz and orthoclase.

Quartz.—The quartz grains, which generally composes 97 per cent or more of the St. Peter sandstone, range in size from medium to fine. The larger grains are well-rounded and frosted, whereas the smaller grains tend to be more angular and glassy. Secondary enlargement, with the later quartz in optical continuity with the original grain shown by a dust film, is not uncommon.

Feldspar.—Orthoclase occurs as small euhedral crystals, 0.04 mm. or less in diameter, and rarely as irregularly shaped detrital grains. The crystals include the following forms: the base 001, the clino pinacoid 010 and the prism 110. In many of the crystals the basal pinacoid is strongly developed with the elongation parallel to *a*. The crystals contain no sign of a nucleus and appear to be homogeneous throughout. Reddish-brown and black irregular inclusions are rather common, but the grains are rarely clouded. The crystals have the following optical constants as determined by the double variation method of refractive index, described by Emmons (22).

$N_g = 1.524$	$N_g - N_p = .006$ Sign $(-)$.
$N_m = 1.522$	$2V$ Obs. 68°
$N_p = 1.518$	$2V$ Cal. 74°

These indices should be accurate to within one in the third place. From the optical data the feldspar appears to be adularia. Feldspar was not found to exceed two per cent in the samples examined, however, this mineral was not studied in all the samples collected.

Glauconite.—Glauconite is common in the Glenwood horizon where it occurs as a very fine dust giving the sandstone and shale a green color. It is also present as irregular masses filling the spaces between quartz grains and forming small balls of dark green glauconite-cemented sandstone. Thin sections of these balls show the glauconite in intimate relation with limonite and jarosite. The X-ray pattern of the "glauconite" from the Glenwood horizon checks the standard glauconite pattern exactly.

Heavy Minerals.—The heavy minerals constitute a minor fraction, 0.005 to 0.05 per cent by weight, of the St. Peter sandstone. The following minerals with a specific gravity greater than 2.96 were identified; anatase, apatite, celestite, ceylonite, dahllite, garnet, ilmenite, jarosite, leucoxene, marcasite and py-

rite, rutile, staurolite, tourmaline and zircon.

Anatase.—Both yellow and blue anatase are present, but the yellow variety is much more abundant. Basal, tabular grains often bevelled by pyramidal faces are most common. Zoning is well developed in most grains, and many of the crystals are filled with opaque, dust-like inclusions. The euhedral form of the anatase as well as the fact that crystals are frequently seen projecting from leucoxene grains indicates that the anatase is authigenic. The crystals average about 0.08 mm. in diameter.

Apatite.—Detrital apatite in the form of colorless, unaltered, spherical to elliptical grains is a rare constituent. Black and colorless inclusions are present, but are never abundant.

Celestite.—Celestite, almost always free of inclusions, is present as angular, colorless fragments and occasional subangular grains. It is not uncommon to find celestite which has included or partially grown around quartz grains and many of the celestite grains bear impressions of other grains indicating that the celestite has served as a cement. Crystals of this mineral, although rare, are present. Occasional grains have inclusions of opaque reddish-brown or black material. The grains range from 0.06 mm. to 0.5 mm. in diameter.

Ceylonite.—The ceylonite ranges in color from a deep emerald to a somewhat lighter green and is present as spherical or elliptical grains about 0.1 mm. in diameter. Occasional grains contain colorless, needle-like inclusions. The refractive index as determined on several grains is about 1.720. The surfaces of all the ceylonite grains are very finely etched.

Dahllite.—This mineral occurs as hexagonal crystals, consisting of the prism and base, which are clouded with fine yellowish dust-like inclusions. With reflected light the crystals have a rather light yellowish waxy appearance. The mineral has the following optical constants.

$N_0 = 1.619$ $\quad N_0 - N_e = .010$
$N_e = 1.609$ $\quad$ Sign(−).

The largest crystals are about 0.04 mm. in length. Some of the sandstone samples contain one-half of one per cent of dahllite or more.

Garnet.—The garnet is in the form of colorless or pink, angular grains, with deeply etched and pitted surfaces. Colorless, brown and black inclusions are occasionally present. The grains range from 0.08 mm. to 0.4 mm. and average about 0.16 mm. in diameter.

Ilmenite.—Ilmenite may be confused with black or dark brown tourmaline, but the following distinctions are generally sufficient to differentiate the two minerals: (1) tourmaline is present as "biscuit-shaped" grains whereas ilmenite is in the form of almost spherical grains with smooth surfaces, which are characteristically pitted, or as rather angular particles; (2) under crossed nicols with the condensing lens inserted, the thin edges and margins of the black and dark brown tourmaline grains almost always transmit some light, the ilmenite does not; (3) practically all of the grains identified as ilmenite are in various stages of alteration to leucoxene. Inasmuch as a complete gradation from ilmenite to leucoxene exists, the personal factor is introduced as to whether a given grain should be classed as leucoxene or ilmenite. The "ilmenite" was X-rayed and found to check the standard ilmenite pattern. The grains average about 0.1 mm. in diameter. It is recognized that in some samples other opaque minerals may be included with the ilmenite.

Jarosite.—The jarosite consists of small, tabular yellow crystals composed of the rhombohedron and the basal pinacoid. The crystals appear to be uniaxial negative with N_0 about 1.820 and N_e about 1.714. However, a basal section examined on the universal stage shows the mineral to be biaxial, with $2V$, 12 degrees. The crystals, generally smaller than 0.03 mm., are pleochroic from golden yellow to colorless, readily soluble in hydrochloric acid, but insoluble in water. The X-ray pattern checks exactly with the pattern obtained from a jarosite specimen, 60976 University of Wisconsin Geological Museum, collected at Dividend, Utah.

Leucoxene.—Leucoxene appears as smooth, rounded grains, and also as white to brown, porous, earthy grains. The surface of the smooth, rounded grains suggests a detrital origin, whereas the porous, earthy grains are thought to represent alteration of ilmenite *in situ*. Frequently small tablets of anatase are seen projecting from leucoxene grains. Many

of the rounded and polished grains of leucoxene were broken open with a needle and found to contain a core of ilmenite. In no case was rutile observed altering to leuxocene. The leucoxene grains average about 0.1 mm. in diameter.

Pyrite.—Pyrite is present as octahedra, cubes and pyritohedra as well as clusters and aggregates. Some of the irregular iron sulphide clusters are undoubtedly marcasite, but no distinction was made.

Rutile.—Rutile occurs as fox-red euhedral grains, as prismatic grains with well rounded terminations and as rounded irregularly shaped grains.

Staurolite.—Angular, straw-yellow grains which have a hackly surface are characteristic of this mineral. In general, colorless and opaque inclusions are very abundant.

Tourmaline.—The dominant color of the grains is brown, with the green variety next most abundant. Blue and colorless grains are rather rare. The brown type ranges from a deep brown, through yellow brown, orange and yellow to colorless. The green tourmaline grades almost imperceptibly from a fine green through a brownish-green to brown and black. The blue grains range from deep blue to pale blue. Occasional parti-colored brown and blue, brown and green, or blue and green grains are present. Most of the grains are free from inclusions. Inclusions present are long needle-like crystals, irregular colorless inclusions and opaque angular masses. Many of the grains show the development of fine etching when viewed with the high power objective. The etching is much the same as that described by Fraser (23) from the basal Ordovician sandstones of Ontario and Quebec. The etching seems to be generally confined to either one or both ends of the "c" axis, although occasional grains are present in which the entire grain appears to be etched. The internal angle of the etched lines is about 130 degrees. The etching probably has taken place, as suggested by Fraser, along planes parallel to the rhombohedral faces. The tourmaline grains are, in general, elliptical or biscuit-shaped. Some grains have striations parallel to the direction of elongation. The grains range from 0.08 mm. to 0.4 mm. and average 0.1 mm. in diameter.

Zircon.—Roughly spherical and prismatic grains with well rounded terminations are most abundant, although prismatic grains with pyramidal terminations are not rare, especially in the smaller sizes. The surfaces of the grains are pitted and frosted to a moderate degree. The color ranges from pink, brown and slightly yellowish to colorless. The gradation from colored to colorless zircon is so complete that it is difficult to differentiate the various shades, thus the per cent of pink zircon as given in the tables is subject to a personal factor. The pink zircon of the St. Peter sandstone seems to be the same shade as that described by Mackie as "purple" in his study of the heavy minerals of the Lewisian gneiss and the sedimentary rocks of Scotland. Mackie[24] states that, "In regard to colour, they vary from only a faint purplish or pinkish tint to an intensity which renders the crystal nearly opaque."

Zoning, although rather rare, is very well developed in some grains. It is not confined to any particular shade or type of grain. Colorless and opaque inclusions are common, but do not cloud the grains. A rather small per cent of the grains contain fractures. The zircon ranges in size from 0.03 mm. to about 0.25 mm. and averages about 0.1 mm.

Explanation of the Heavy Mineral Table.—The following tables give the detailed heavy mineral data of the St. Peter sandstone inWisconsin.

The relative percentages were determined by counting 300 to 600 grains in each slide. The per cent of pyrite, as well as celestite and jarosite, was estimated rather than determined by count, because of the tendency of these minerals to flood the samples. The following letter key is used in tabulating estimated per cent.

		per cent			per cent
Flood	F	75–100	Present	P	5–10
Dominant	D	50–75	Rare	R	1–5
Abundant	A	25–50	Trace	X	less than 1
Common	C	10–25			

TABLE 1.—*Heavy Minerals of the St. Peter Sandstone in Wisconsin. Belleville Section, Samples 1A to 17A; Bridgeport Section, Samples 1N to 17N*

Sample No.	Tourmaline (Total)	Brown	Green	Blue	Colorless	Zircon (Total)	Colorless	Pink	Garnet (Colorless)	Pink	Ceylonite	Anatase	Apatite	Rutile	Staurolite	Leucoxene	Ilmenite	Pyrite	Jarosite
1A*	15	13	2			28	20	8				16				38	3	P	
2A	18	13	5	X		69	48	21				X				10	3	P	
3A	26	17	9	X		58	38	20								14	2	P	
4A	10	7	3	X		32	25	7				4				53	1	P	
5A	11	6	5	X		34	24	10				1				52	2	P	
6A	25	16	9			28	19	9				9				36	2	P	
7A	27	17	10	X		23	16	7				14				35	1	P	
8A	22	12	10	X		26	20	6				3				47	2	P	
9A	17	11	6	X		34	28	6				2				45	2	P	
10A	12	7	5	X		29	22	7			X	2				56	1	P	
11A	12	8	4	X		37	31	6			X	5				45	1	P	P
12A	10	7	3			32	24	8				4				53	1	P	
13A	11	7	4	X		40	28	12				3				45	1	P	P
14A	23	13	10	X		33	25	8				6				36	2	P	
15A	12	6	6			40	30	10				X				43	5	P	
16A	18	9	8	1		34	27	7				2				45	1	P	
17A	24	15	8	1		24	17	7				3				47	2	P	
1N*	X	X	X			100	90	10	X		X					X	X	P	
2N	3	2	1	X		95	87	8			X					1	1		
3N	5	5	X	X		92	83	9			X	X				X	3		
4N	6	4	2	X		94	84	10			X					X	X		
5N	11	9	2	X		87	77	10			X		X			1	1		
6N	8	6	2	X		86	77	9								5	1		C
7N	15	14	1	X		81	74	7	X		X					2	2		P
8N	13	12	X	1	X	83	71	12			X	X				X	4		
9N	15	13	2	X		79	70	9			X		X	X		2	4	P	P
10N	9	6	3	X		82	71	11			X					6	3	P	
11N	7	5	2	X	X	82	70	12			X			X		9	2	P	P
12N	X	X	X			98	85	13			X					1	1		
13N	X	X	X			100	92	8						X		X		P	P
14N	X	X	X		X	95	87	8			X			X		5			
15N	X	X	X			98	90	8					X			1	1		
16N	X	X	X	X		98	89	9				X				1	1		
17N	10	8	2	X	X	86	76	10						X	X	2	2		

* Top of St. Peter—first 2 feet of sandstone beneath the Platteville dolomite.

Discussion of the Heavy Mineral Analyses.—Tables 1 to 8 inclusive show that zircon, tourmaline, leucoxene, ilmenite, anatase, pyrite, apatite, rutile, garnet, staurolite, celestite, ceylonite, jarosite and dahllite comprise the heavy mineral suite of the St. Peter sandstone in Wisconsin. Zircon and tourmaline are the dominant allothogenic minerals, with ilmenite and its alteration product leucoxene common, but less abundant. Apatite, rutile, staurolite, garnet and ceylonite are rather rare constituents. The authigenic minerals, anatase, pyrite, jarosite, celestite

TABLE 2.—*Heavy Minerals of the St. Peter Sandstone in Wisconsin. Blue Mounds Section, Samples 1M to 39M*

Sample No.	Tourmaline (Total)	Brown	Green	Blue	Colorless	Zircon (Total)	Colorless	Pink	Garnet (Colorless)	Pink	Ceylonite	Anatase	Apatite	Rutile	Staurolite	Leucoxene	Ilmenite	Pyrite	Jarosite
1M*	X	X	X			98	78	20			X	X		X		1	1	P	
2M	8	6	2	X		82	57	25								7	3	P	
3M	25	23	2	X		54	27	27								15	6	P	
4M	57	51	6			17	12	5								8	18		
5M	50	45	5	X		33	22	11				X				9	8	P	
6M	21	14	7	X		73	48	25			X	1				2	3	P	
7M	38	30	8	X		55	36	19			X	X			X	2	5	P	
8M	33	22	11	X	X	58	33	25			X	X			X	3	6	P	
9M	58	46	12	X		32	17	15	X			X			X	2	8		
10M	52	33	19	X		41	28	13				X		X	X	2	5	P	
11M	24	17	7	X		71	37	34				X			1	1	3	P	
12M	28	16	12	X		70	44	26							X	X	2	P	
13M	14	9	5	X		59	33	26			X	X			X	19	8	P	
14M	1	1	X			90	43	47							4	1	4	P	
15M	5	3	2			92	60	32			X				X	1	2		
16M	27	17	10	X		45	22	23				X			2	21	5	P	
17M	34	20	14	X		60	35	25			X	X			X	X	6	P	
18M	19	11	8	X		46	27	19			X	X			X	31	4	P	
19M	15	13	2	X		25	14	11							X	56	4	C	
20M	6	5	1	X		87	42	45				X			X	6	1	P	
21M	23	15	8	X		43	27	16				6			X	20	8	P	
22M	4	3	1			57	29	28							X	38	1		
23M	8	8		X		56	29	27							X	33	3	P	
24M	17	14	3		X	29	18	11							X	51	3	P	
25M	11	8	3			36	18	18				3			X	50		P	
26M	19	16	3			23	15	8	X						X	58			
27M	5	4	1			30	17	13								65			
28M	1	1				41	24	17				1				57		P	
29M	12	6	6			36	22	14				X				52		P	
30M	6	2	4	X		30	19	11				X				63	1	P	
31M	5	3	2	X		28	13	15				2				62	3		
32M	X	X				47	24	23	X							53		P	
33M	15	12	3	X		30	14	16				5				46	4	P	
34M	4	4	X			47	32	15				4				44	1		
35M	6	3	3	X		28	19	9				4			X	60	2	P	
36M	X	X				24	17	7				2			X	73	1	P	
37M	2	2				48	36	12							X	50	X	P	
38M	2	2	X			50	36	14				1				46	1	P	
39M	6	4	2	X		30	22	8				35				29		P	

* Top of St. Peter.

and dahllite are more or less sporadic in their occurrence.

The allothogenic heavy mineral suite of the St. Peter sandstone exhibits regional as well as stratigraphic variation in the relative per cent of constituent minerals, but does not vary appreciably as to the presence or absence of species. Leucoxene, although an alteration product of ilmenite, is considered as a part of the allothogenic suite, because leucoxene

TABLE 3.—*Heavy Minerals of the St. Peter Sandstone in Wisconsin. Browntown Section, Samples 1S to 26S, Burke Section; Samples, 1Y to 7Y; Rockdale Section, Samples 1F to 2F and 1R to 5R; Two Rivers Section, Samples 16816*

Sample No.	Tourmaline (Total)	Brown	Green	Blue	Colorless	Zircon (Total)	Colorless	Pink	Garnet (Colorless)	Pink	Ceylonite	Anatase	Apatite	Rutile	Staurolite	Leucoxene	Ilmenite	Pyrite	Jarosite	Clestite
1S*	20	16	3	1		49	42	7		X		9				19	3	C	C	
2S	39	37	1	1		41	21	20				2				12	6	C	A	
3S	6	5	1	X		80	72	8								13	1	C	A	
4S	23	21		2		67	36	31	X							5	5	P	C	
5S	12	11		1		82	50	32								1	5	C		
6S	8	8				90	62	28								1	1	A		
7S	23	22	1	X		74	46	28								2	1	P		
8S	48	42	5	1		48	35	13								2	2	P		
9S	14	10	4	X		79	49	30		X						3	4	C		
10S	10	6	4	X		88	67	21								1	1			
11S	13	8	5			83	62	21				X				1	3	P		
12S	31	18	13	X		61	41	20								3	5	P		
13S	31	29	X	2		60	46	14	X			X	X			5	4	P		
14S	22	21	1	X		73	48	25			X					2	3	P		
15S	28	23	5	X		61	36	25								8	3	P		
16S	14	11	3			57	37	20								27	2	P		
17S	9	9				80	46	34								11		P		
18S	6	6	X	X		90	63	27								3	1	P		
19S	19	18		1		78	48	30								1	2			
20S	3	3		X		17	10	7					X			80	X	P		
21S	3	3	X			18	10	8			X					79	X	P		
22S	2	2	X			33	21	12								65	X			
23S	2	2	X			22	15	7								76		C		
24S	1	1				25	15	10								74	X	P		
25S	3	3				35	22	13								61	1	P		
26S	2	2	X	X		21	14	7	X	X						77	X	P		
1Y	8	5	3	X		43	39	4				20				1	28			
2Y	15	11	4	X		15	13	2				12				12	46	P		
3Y	3	2	1	X		18	15	3				2				3	74			
4Y	10	6	4			49	40	9				1				3	37			
5Y	2	1	1			26	23	3			X	8		X		2	62			
6Y	9	7	2	X		21	18	3				9	X			9	52			
7Y	6	5	1			26	23	3				3	X		X	1	64	P		
1F*	4	3	1			91	85	6								3	2	P		
2F	6	5	1			90	80	10		X						1	3	P		
1R	20	13	6	1		41	36	5				2				33	4	P		
2R	18	13	4	1		48	40	8				1				30	3	P		
3R	20	16	3	1		50	44	6				1				27	2	P		
4R	25	17	7	1		59	53	6	X			1		X		13	2	P		
5R	8	6	2	X		85	77	8								6	1	P		
16816						96	88	8								2	2	D		C

* Top of St. Peter.

TABLE 4.—*Heavy Minerals of the St. Peter Sandstone in Wisconsin. Cedarburg Section, Sample 70267; Dellona Section, Sample 1D; Depere Section, Sample 75771 to 75772; Franksville Section, Samples 81057 to 81071; Gibraltar Bluff Section, Samples 4H to 1H; Koshkonong Section, Samples 1K to 6K*

Sample No.	Tourmaline (Total)	Brown	Green	Blue	Colorless	Zircon (Total)	Colorless	Pink	Garnet (Colorless)	Pink	Ceylonite	Anatase	Apatite	Rutile	Staurolite	Leucoxene	Ilmenite	Pyrite	Jarosite	Celestite
70267	6	6	X			86	77	9			X					2	6	C	R	
1D	10	8	2			29	26	3				X		X		X	61			
75771	7	5	2			77	71	6	X							13	3	C		R
75772	6	5	1	X		75	66	9	X							4	15	C		R
81057*	2	1	1			93	87	6	X	X				X		3	2	F		
81058	11	7	4	X		84	77	7	X	X				X		X	5	F		
81059	14	9	5	X		75	69	6	X							1	10	F		
81060	39	29	9	1		57	52	5	X			X				1	3	A		
81061	20	14	5	1		76	69	7								1	3	A		
81062	10	8	2	X		82	75	7								2	6	D		
81063	2	1	1			92	80	12								2	4	F		
81064	8	4	4	X		87	74	13	X					X		1	4	D		
81065	13	6	6	1		78	71	7						X		2	7	A		
81066	19	13	6	X		78	72	6								1	2	A		
81067	15	10	5	X		81	74	7						X		1	3	D		
81068	4	2	2	X		90	84	6				X		X		2	4	A		
81069	X	X	X			90	79	11						X			10	F		
81070	5	2	3	X		84	74	10	X			X		1		2	8	F		
81071	5	2	3	X		80	65	15	X			X		1		4	10	F		
4H	21	19	2	X	X	32	31	1					X			44	3	R		
3H	17	15	1	1		50	47	3								31	2	R		
2H	15	12	3	X		44	42	2				1				38	2	R		
1H	11	9	2	X	X	50	48	2			X	2		X		33	4	P		
1K	29	25	3	1		67	62	5								3	1	P		
2K	35	26	8	1		62	57	5								1	2			
3K	27	19	4	4		71	63	8								X	2	P		
4K	47	35	10	2		47	43	4								2	4	P		
5K	47	30	13	4		48	45	3								3	2	C		
6K	46	34	9	3		49	42	7								3	2	A		

* Top of St. Peter.

occurs as a grain for grain alteration of the original ilmenite. The terms stratigraphic and regional variation are used here in the sense of a general change in the relative per cent of the constituent minerals over a number of samples, and does not mean sample to sample variation.

Stratigraphic variation is well shown in the Browntown, Blue Mounds and River Falls sections (see Tables 2, 3, and 8). It is difficult to determine the frequency, extent and continuity of heavy mineral zones in the St. Peter, for most of the sections include only a part of the

TABLE 5.—*Heavy Minerals of the St. Peter Sandstone in Wisconsin. Lake Mills Section, Samples 1Z to 9Z; Lancaster Section, Samples 1L to 12L, 1AL to 7AL and XL; Marinette Section, Samples 1V to 4V*

Sample No.	Tourmaline (Total)	Brown	Green	Blue	Colorless	Zircon (Total)	Colorless	Pink	Garnet (Colorless)	Pink	Ceylonite	Anatase	Apatite	Rutile	Staurolite	Leucoxene	Ilmenite	Pyrite	Jarosite
1Z*	30	23	6	1		62	53	9				X				3	5		
2Z	19	15	3	1		73	60	13				1				5	2		
3Z	16	12	4	X		78	66	12								3	3		
4Z	19	14	4	1		69	59	10				X				8	4		
5Z	24	19	4	1		62	52	10				X				10	4		
6Z	18	15	3	X		66	58	8				X				10	6		
7Z	11	7	4	X		46	41	5				11				29	3	P	
8Z	6	3	3	X		54	47	7				12				27	1		
9Z	4	2	2	X		42	38	4				16				37	1		
1L*	1	1	X	X		97	90	7	X		X					1	1		
2L	15	14	1	X	X	83	78	5			X			X		X	2		
3L	3	2	1			95	89	6						X		1	1		
4L	4	3	1	X		56	50	6				X				39	1		P
5L	11	9	2	X	X	79	73	6			X	X				10	X	P	P
6L	7	5	2		X	55	50	5								37	1		
7L	19	14	5	X	X	76	67	9			X			X		3	2		P
8L	18	13	5	X	X	52	47	5								28	2		
9L	11	7	3	1	X	75	68	7						X		12	2		
10L	16	11	5	X	X	72	67	5						X		11	1		P
11L	11	6	5	X	X	77	69	8			X			X		11	1		P
12L	9	6	3	X	X	87	78	9			X			X		3	1	P	P
1AL	15	9	6	X	X	80	70	10						X		2	3	P	P
2AL	10	6	4	X	X	87	80	7						X		1	2		P
3AL	9	6	3	X		87	80	7			X			X		1	3		P
4AL	8	5	3	X	X	89	81	8			X			X		1	2		
5AL	11	7	4	X		85	74	11			X	X		X		1	3		P
6AL	11	6	5	X		88	75	13			X			X		X	1		P
7AL	13	9	4	X		83	71	12			X			X		1	3		
XL	30	17	13	X		59	52	7			X			1		7	3	P	P
1V	32	27	4	1		49	44	5				6	X	X		10	3	D	
2V	8	6	2	X		83	78	5				4		X		4	1	D	
3V	16	12	4	X		59	55	4				5				19	1	C	
4V	8	6	2	X		72	63	9				6				13	1	D	

* Top of St. Peter.

total thickness of the formation. It is interesting to note, however, that the high ilmenite-leucoxene sands of south-central Wisconsin are encountered some distance below the top of the formation at Blue Mounds and Browntown.

Figure 1 shows the leucoxene-ilmenite areal distribution of the St. Peter sandstone in Wisconsin. Each number appearing on the map is an average of the per cent of leucoxene-ilmenite in that portion of the section sampled. The Blue Mounds, Gibral-

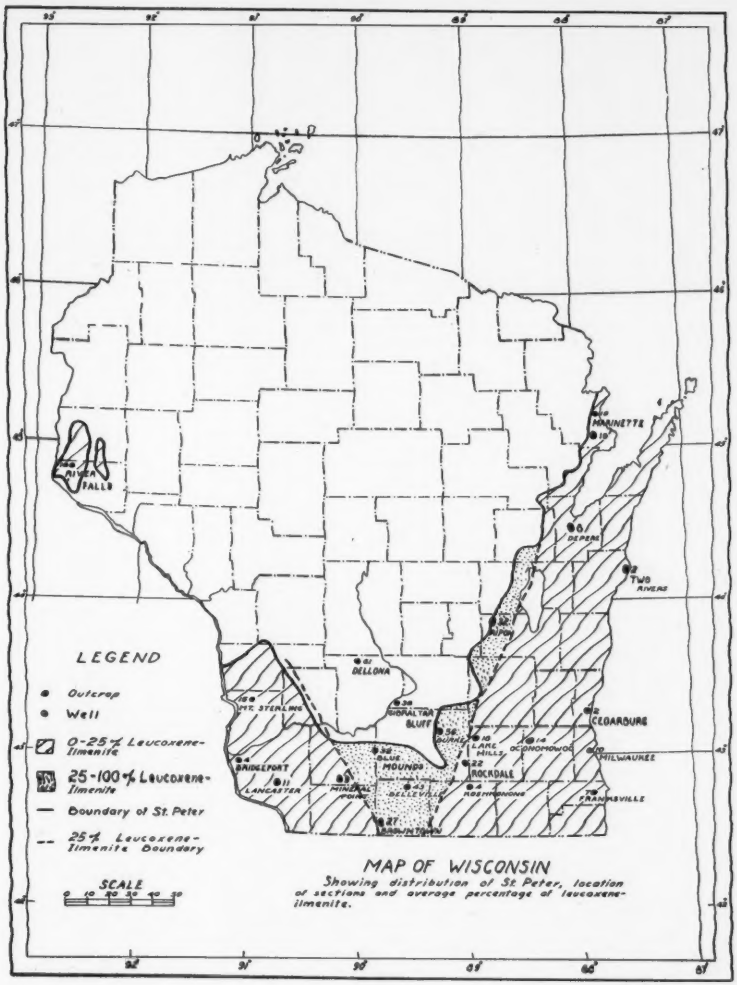

FIG. 1

tar Bluff, Burke, Belleville, Browntown and Ripon sections contain the largest relative per cent of leucoxene-ilmenite. The relative percentages of these minerals decreases both to the east and to the west of the south central part of the state. As leucoxene-ilmenite decreases, zircon increases

TABLE 6.—*Heavy Minerals of the St. Peter Sandstone in Wisconsin. Mineral Point Section, Samples 1P to 13P; Mount Sterling Section, Samples 1C to 9C; Ripon Section, Samples 1B to 19B*

Sample No.	Tourmaline (Total)	Brown	Green	Blue	Colorless	Zircon (Total)	Colorless	Pink	Garnet (Colorless)	Pink	Ceylonite	Anatase	Apatite	Rutile	Staurolite	Leucoxene	Ilmenite	Pyrite	Jarosite
1P*	4	3	1	X	X	94	86	8	X	X	X	X				1	1	P	
2P	29	22	6	1	X	63	54	9	X			1				1	6	P	
3P	54	43	11	X	X	37	29	8								1	8	P	
4P	43	30	12	1		49	42	7								1	7	P	
5P	33	24	8	1	X	57	47	10								2	8		
6P	45	36	9	X		49	42	7								1	5	P	P
7P	37	28	9	X		55	49	6								2	6		
8P	38	29	9	X	X	51	42	9								3	8		
9P	43	38	4	1	X	40	26	14			X					6	11		
10P	22	18	4			67	53	14				X				4	7	P	
11P	49	31	17	1		43	33	10			X					X	8	P	
12P	47	33	13	1		47	38	9				X				X	6		
13P	42	31	11	X		47	41	6				X				1	10		
1C*	10	6	4	X	X	65	60	5		X					X	24	1	P	
2C	12	6	6	X	X	82	72	10								3	3	P	
3C	5	5	X	X		90	83	7			X			X		3	2		
4C	7	6	1	X	X	71	67	4			X			X		20	2	P	
5C	8	8		X	X	74	70	4				X		X		16	2		
6C	2	2	X	X		94	89	5			X					3	1		
7C	2	2	X			86	81	5								11	1		
8C	1	1	X	X		89	85	4			X	X				9	1	P	
9C	4	3	1	X		64	62	2				X		X		31	1	P	
1B*	6	3	3	X		55	47	8	7	4				X		26	2	P	P
2B	5	2	3	X		56	49	7		X				2		35	2	P	P
3B	18	12	5	1		63	51	12						2		14	3		
4B	10	6	4	X		69	56	13	1					X		18	2	P	
5B	19	8	11	X		66	54	12								12	3	P	P
6B	32	6	26			28	24	4	8							16	16	P	
7B	38	13	25			46	34	12	X							10	6	P	
8B	9	3	6	X		34	28	6	2			X			X	52	3	P	
9B	14	4	10			37	28	9	2							42	5	P	
10B	7	4	3	X		41	34	7	X		X			X		45	7	P	P
11B	17	11	6	X		42	36	6	X					X	X	39	2	P	
12B	18	11	7	X		46	38	8	1			X		X		33	2	A	
13B	7	4	2	1		59	52	7						1		30	3		P
14B	12	7	5	X		57	50	7	X					X		27	4	P	
15B	12	7	4	1		43	37	6				4		X		38	3	P	P
16B	17	12	5	X		41	36	5	2			X				38	2	P	
17B	11	8	3	X		32	29	3								56	1	P	P
18B	26	17	8	1	X	69	59	10	X							4	1	P	P
19B	15	9	5	1		81	72	9				X		X		2	2	P	

* Top of St. Peter.

TABLE 7.—*Heavy Minerals of the St. Peter Sandstone in Wisconsin. Oconomowoc Section, Samples 74458 to 74475 from the St. Peter sandstone, 74476 to 74479 from the Franconia sandstone; Milwaukee Section, Samples 81365, 81405 to 81410 incl., from the St. Peter sandstone, 81487 from the Mt. Simon sandstone*

Sample No.	Tourmaline (Total)	Brown	Green	Blue	Colorless	Zircon (Total)	Colorless	Pink	Garnet (Colorless)	Pink	Ceylonite	Anatase	Apatite	Rutile	Staurolite	Leucoxene	Ilmenite	Pyrite	Jarosite	Celestite
74458*	X	X				91	82	9	X	X	X						9	P		
74459	9	5	4	X		74	70	4	X	X						3	14	C		
74460	4	3	1			87	76	11	1							1	7	P		
74461	7	5	2	X		70	57	13	X	X	X					7	16	A		
74462	12	7	5	X		73	61	12	X						X	2	13	A		
74463	28	17	10	1		58	52	6								2	12	A		
74464	23	14	8	1		69	60	9	X	X		X				2	6	A		
74465	7	5	2			81	73	8	X							1	11	F		
74466	8	6	2			87	78	9								X	5	F		
74467	25	13	11	1		52	47	5								1	22	D		
74468	2	1	1		X	49	47	2	X					X	X	2	47	F		
74469	8	6	2			68	56	12	X				X			1	23	F		
74470	8	4	4	X		82	67	15									10	F		
74471	10	7	3	X		80	70	10		X			X			1	9	F		
74472	22	10	10	2		69	53	16	X							2	7	D		
74473	24	10	14	X	X	71	60	11	X	X	X			X		1	4	F		
74474	17	7	10			79	73	6	X							1	3	F		
74475	12	5	7			78	61	17	X					1		1	8	F		
74476[a]	1	1	X	X		17	14	3	65	14						1	2	D		
74477	2	1	1	X		23	20	3	67	6						X	2	D		
74478	10	5	5			58	51	7	22	5				1		2	2	F		
74479	9	4	5			65	55	10	16	1		X		1		4	4	F		
81365	7	6	1		X	86	78	8	X			1				2	4	C		A
81405	5	5	X	X		83	78	5								1	11	A		F
81406	5	3	2			90	79	11			X					1	4	A		D
81407	3	2	1			92	83	9						X		1	4	A		A
81408	2	1	1			91	87	4								2	5	C		C
81409	5	4	1			79	69	10								2	14	A		F
81410	1	1	X			84	74	10						X		8	7	A		F
81487	7	7				83	80	3	X			X				3	7	C		F

[a] Top of Franconia.
* Top of St. Peter.

until to the west it reaches a maximum of 90 per cent at Bridgeport, and to the east a maximum of 96 per cent at Two Rivers, 86 per cent at Milwaukee and Cedarburg, and 82 per cent at Franksville.

Tourmaline does not show a consistent regional variation, but is more or less uniform. The general uniformity of the heavy mineral suite over wide areas may be readily seen by inspecting tables 1 to 8 inclusive.

Celestite, which apparently occurs primarily as a cement in the St. Peter sandstone is present at the following localities: Depere, Cedar-

TABLE 8.—*Heavy Minerals from the St. Peter Sandstone in Wisconsin, River Falls Section, Samples 1E to 38E*

Sample No.	Tourmaline (Total)	Brown	Green	Blue	Colorless	Zircon (Total)	Colorless	Pink	Garnet (Colorless)	Pink	Ceylonite	Anatase	Apatite	Rutile	Staurolite	Leucoxene	Ilmenite	Pyrite	Jarosite
1E*	X	X				58	52	6	1	37						2	2	P	
2E	1	1	X	X		54	46	8	X	32						10	3	P	
3E	X	X		X		43	35	8	X	27				X		20	10	P	
4E	X	X	X			90	77	13		X	X	X				8	2	C	
5E	X	X	X	X	X	96	83	13		X	X					2	2		
6E	2	1	1			30	24	6							X	61	7		
7E	1	1	X	X		67	52	15							X	31	1	P	
8E	1	1	X			63	52	11							X	34	2	P	
9E	X	X	X			47	42	5			X				X	51	2	P	
10E	8	8	X			42	31	11							X	49	1	P	
11E	3	3	X	X		63	45	18			X				X	34	X	P	
12E	7	4	3	X		74	54	20		X	X				X	17	2	C	
13E	6	3	3			74	60	14							X	19	1	P	
14E	30	20	10			46	37	9							X	19	5	C	
15E	11	8	3	X		55	42	13							X	34	X	C	
16E	9	9	X	X		55	46	9			X	X			X	31	5	P	
17E	14	9	5			78	62	16		X					X	4	4	C	
18E	18	11	7			69	55	14						X	X	9	4	C	
19E	36	28	8	X		54	40	14			X				X	5	5	A	
20E	31	21	10	X		54	44	10							X	6	9	C	
21E	64	50	14	X	X	22	18	4							X	2	12	C	
22E	59	38	19	2		26	18	8							X	6	9	A	
23E	32	22	10	X		59	48	11							X	3	6	D	
24E	27	20	7			59	51	8				X			X	7	7	F	
25E	15	12	3	X		68	50	18							X	3	14	D	
26E	17	11	6	X		76	59	17							X	X	7	C	
27E	39	24	14	1		45	36	9			X	X	X		X	8	8	F	
28E	29	15	14	X		61	43	18						X	X	5	5	D	
29E	43	24	19			36	24	12						X	X	2	19	F	
30E	14	12	2	X		76	49	27						X	X	3	7	A	
31E	13	9	4			81	36	45							X	4	2	P	
32E	24	17	6	1		67	19	48				X	X	X	X	3	6	C	
33E	15	9	6	X	X	78	31	47			X	X		X	X	2	5	C	
34E	24	16	8	X		62	17	45				X		X	X	9	5	C	
35E	9	7	2			84	29	55			X	X		X	X	2	5	C	
36E	18	14	4	X		72	24	48			X			X	X	5	5	C	
37E	14	9	5	X	X	79	27	52			X			X	X	4	3	C	
38E	33	24	8	1		49	20	29		X				X	X	9	9	A	

* Top of St. Peter.

burg, Two Rivers and Milwaukee. At Milwaukee celestite was noted in the Mt. Simon sandstone (see Table 7) so that evidently it is not confined to the St. Peter sandstone.

Garnet seems to be a rather rare constituent of the St. Peter sandstone. In only three samples studied does it occur in any abundance, and these are located not in the St. Peter but in the Glenwood horizon at River Falls. Mackie (25) suggests that garnet may be removed by solution, but this does not seem to be the case

at Oconomowoc where the St. Peter rests upon the Franconia. The contact is marked by a chert conglomerate; above the conglomerate garnet is very rare, whereas the conglomerate and the underlying Franconia contain abundant garnet (see Table 7). If solution removed the garnet from the St. Peter it is difficult to understand why the garnet was not also removed in the conglomerate and Franconia. The fact that the conglomerate contains a higher per cent of garnet than the underlying Franconia may be due to concentration on the pre-St. Peter erosion surface of the garnet from the Franconia.

It may be assumed, in view of the fact that the St. Peter sandstone is a porous formation and an aquifer, that garnet would be eliminated by carbonated waters. On the other hand, equally porous sandstones, the Ironton and Jordan of Wisconsin are characterized by dominant garnet in their heavy mineral suites. The Ironton and Jordon are older deposits than the St. Peter and thus have had a longer history since deposition during which the garnet would be susceptible to elimination by solution.

If the St. Peter were derived from the Jordan or Franconia it might be expected that mechanical abrasion of the skeleton garnets (the skeleton form being the result of solution) would entirely destroy the mineral. However, an examination of the detrital garnet in these sandstones indicates that most of the grains are not skeleton forms, although they generally are etched. Abrasion of the grain sufficient to destroy that portion of the garnet which had been etched would produce smaller grains, but not necessarily eliminate the garnet. It is also probable that the garnet in the Cambrian deposits was not etched to the present degree at the time of deposition of the St. Peter sandstone.

The Oconomowoc well section shows clearly that where well samples are carefully taken, heavy mineral data are of value in distinguishing the boundaries of formations provided the mineral suites are distinctive.

A study of four samples of the Gibraltar Bluff section failed to show the presence of garnet as reported by Wanenmacher (17) (see Table 4), but contained the normal St. Peter suite. It is thought that Wanenmacher's samples probably included contaminated surficial material or that a mistake was made in labeling samples.

Jarosite is of far more common occurrence throughout the samples studied than the mineral tables indicate. The small jarosite crystals, less than 0.04 mm. in diameter, remain suspended in the heavy liquid, and for this reason the mineral was not detected in many samples in which it is undoubtedly present. Jarosite is most abundant in the yellow zones directly beneath the glauconite-bearing Glenwood horizon and also in the Glenwood beds where the glauconite gives way to yellow, iron stained beds. Emmons (26) states that jarosite is often mistaken for limonite, and is a common oxida-

tion product of iron sulphide, particularly in arid and semi-arid regions. Sulphuric acid produced by the oxidation of pyrite and marcasite may have attacked the glauconite, producing jarosite as an alteration product. The occurrence of jarosite in the Glenwood horizon and the St. Peter, where it has been mistaken for limonite, suggests that the "limonite" of other sedimentary formations should be studied in more detail, in order to determine whether jarosite may not be more common than is generally supposed.

INCLUSIONS WITHIN THE QUARTZ GRAINS

Mackie's General Inclusion Law.— In 1896 Mackie (27) made a very important contribution to the determination of provenance through his study of inclusions within the quartz grains of the sandstones and associated igneous rocks of eastern Moray. He classified the quartz grains on the basis of inclusions into four groups:

1. Grains containing acicular inclusions (fine needle-like inclusions).
2. Grains containing regular inclusions (crystals).
3. Grains containing irregular inclusions (fluid lacunæ with or without gas bubbles).
4. Grains containing no inclusions.

The following method was devised by Mackie to prevent cross classification of grains. When a quartz grain contains inclusions of two or more types the acicular takes precedence and the grain is classified as "acicular" even though inclusions of other types are present. In the same manner regular inclusions take precedence over the irregular type. Mackie states that it is a "fairly general law that acicular and irregular inclusions pre-eminently abound in the quartz of granite; that the regular group is to be found in various proportions, but always in relatively large numbers in the quartz of gneiss and the younger schistose rocks" (27). Several examples of granites and metamorphic rocks are cited which illustrate Mackie's conclusions. He also determined the per cent of the various types of quartz grains within the sands and sandstones of the region and suggested their source as indicated by the inclusions present.

In a study of the Millstone Grit Gilligan (28) used the inclusion criteria developed by Mackie and found "that the deduction from the inclusions is in agreement with that previously made, namely, that the quartz has been derived for the greater part from rocks which have been subjected to pressure." He also states, "In their order of relative abundance, the inclusions may be classed as follows: regular, irregular, acicular, negative."

The writer examined and counted the quartz grains, which contained the various types of inclusions, in three samples of granite, two gneisses and two schists in order to check Mackie's general law. Table 9 gives the results of this study.

The quartz grains of the crystalline rocks were isolated for study according to the following procedure. The rock was crushed through a jaw

crusher and then passed through the rolls, producing a product with a maximum diameter of about one-eighth inch. The crushed rock was then screened through a 20-mesh sieve. In this manner the coarse aggregates and the finer grains were discarded. The fine material is largely composed of fragments of coarser grains, and thus is not suitable for the inclusion study. The grains passing the 20 mesh and retained on the 60 mesh were largely found to be monomineralic, and close to the original grain size of the rock. This material was then examined under a binocular microscope and the quartz grains picked out with a needle and mounted in Canada balsam. About one hundred grains of each sample were isolated in this manner and the inclusions examined using the medium power of the petrographic microscope.

The three granites were found to be characterized by irregular inclusions, with regular inclusions rare to common. The regular inclusions appear to be dominantly apatite with some zircon and titanite.

The quartz grains of the schists are characterized by regular inclusions; this type of quartz grain comprising from 92 to 100 per cent of the quartz.

The quartz grains of the two gneisses studied are of the granitic type in that the irregular inclusion quartz grains are most abundant, with the regular inclusion grains common, and acicular inclusion grains rare to absent. It is to be noted that sample 133 is of the schistose phase of a gneiss, whereas sample 119A is of the granitic phase.

TABLE 9.—*Inclusions in Quartz Grains*

Sample No.		A	I	R	N
328	Red granite, Wausau, Wis.		97	3	
172	Gray granite, Felch, Mich.		68	32	
266	Granite porphyry, Mellen, Wis.	4	65	31	
119A	Granite phase of gneiss, Palmer, Mich.	3	74	23	
133	Schistose phase of gneiss, Big Bay, Mich.		88	12	
473	Vishnu schist, Grand Canyon, Ariz.		8	92	
447	Schist, Inspiration Point, Yosemite National Park			100	

A—Acicular, I—Irregular, R—Regular, N—Negative.

It is evident that the three granite samples and the two schists check Mackie's general law. The gneisses, however, are characterized by irregular inclusions in the quartz, and thus should be classed with the granites rather than the metamorphic rocks. This suggests that perhaps regular inclusions are characteristic of paragneisses and schists and not characteristic of the primary gniesses and schists. More detailed information is needed concerning the inclusions within the quartz of granites and metamorphic rocks before definite conclusions may be reached. A study of the inclusions within quartz and the other minerals composing a granite may also throw some light on the time of crystallization of the minor accessories in igneous rocks.

Mackie's General Inclusion Law Applied to the St. Peter Sandstone.—A study of representative slides of quartz grains from the St. Peter

sandstone gives the following average inclusion index: irregular 77 per cent, acicular 15 per cent, regular 8 per cent. According to Mackie's conclusions this suggests that the quartz was derived largely from a granitic terrane. It is to be noted that practically every grain of the St. Peter sandstone contains some type of inclusion. The irregular inclusions are in a few cases arranged in rows, but generally are distributed throughout the grain. The acicular inclusions consist of very fine needles which typically occur at random throughout the grain. The mineral composition of the acicular inclusions is unknown, but may be rutile as suggested by Mackie.

A Study of the Regular Inclusion Suite.—The regular inclusions which are found in only 8 per cent of the quartz grains are interesting in that these crystals have been protected by the enclosing quartz from mechanical disintegration and chemical decomposition throughout the entire history of the sand grain, regardless of the number of erosion cycles through which it has passed. Thus, the less stable minerals which have been preserved in this manner, give a more complete picture of the heavy minerals of the original source rock.

Procedure.—The following procedure was devised in order to free the inclusions so that they might be identified and counted rapidly. About 200 grams of the sand which had been prepared according to the regular crushing procedure were placed on the 80-mesh screen in a Ro-Tap shaker and screened for 20 minutes. The sand coarser than 80 mesh was then treated with a 50 per cent solution of boiling hydrochloric acid for ten minutes, which cleaned the grains very thoroughly of carbonates and iron oxide. The sample was then washed and dried. Examination of the cleaned sand showed that some small grains were still attached to the larger grains. In order to free these grains the sample was placed in the sieve pan with about 75 grams of glass beads and agitated in the Ro-Tap shaker for one hour or more. The impact of the glass beads in the pan upon the aggregates was sufficient to free most of the grains without any appreciable crushing of the sand. The sample was then placed upon the 80-mesh screen, and screened for 30 minutes. In all cases an appreciable amount of sand finer than 80 mesh was screened out at this stage. The sample was then placed in a separatory funnel and a heavy mineral separation carried out according to the standard procedure, in order to free the quartz grains of the detrital heavy minerals which were coarser than 80 mesh. The lights in this case constitute the sample. The lights were then passed through a disk crusher, with the disks so adjusted, that the grains were crushed finer than 100 mesh, and as far as possible coarser than 200 mesh. The iron filings introduced through the wear on the plates in the disk crusher were removed by passing the powder through a glass tube placed between the poles of an electro-magnet. The fines produced in the crushing process were eliminated by washing the sample in a large

evaporating dish. The material which did not settle within one minute in three inches of water was considered too fine to work with satisfactorily and therefore decanted. After the washing was completed, the sample was placed in an oven and dried at 110°C. The dried sample was then split, and a 50-gram portion separated according to the standard heavy mineral procedure. The heavies were mounted in Canada balsam and studied.

Inclusion Heavy Minerals of the St. Peter Sandstone.—The following inclusion heavy minerals were identified from the quartz grains of the St. Peter sandstone: apatite, biotite, fluorite, garnet, hornblende, ilmenite, kyanite, leucoxene, pyrite, rutile, titanite, tourmaline and zircon.

Apatite.—The apatite is in the form of colorless, elongated prismatic crystals which rarely contain inclusions. The crystals range from 0.016 mm. to 0.16 mm. in length.

Biotite.—Biotite appears as brown to yellowish-green cleavage flakes, some of which exhibit a pseudo-hexagonal outline. The flakes only rarely contain inclusions. The average diameter is about 0.1 mm.

Fluorite.—Colorless, angular fragments without inclusions, are characteristic of this mineral.

Garnet.—Garnet is present only as colorless to pink dodecahedra, which are generally clear and entirely free from inclusions.

Hornblende.—Green to brownish-green elongated cleavage fragments and prismatic crystals are about equally common. The grains are pleochroic from green to yellowish-green and generally do not contain inclusions.

Ilmenite.—Ilmenite occurs as black, irregular, moderately magnetic grains, which are in some cases partially altered to leucoxene. This alteration may have taken place when a portion of the ilmenite inclusion was exposed at the surface of the quartz grain. It is recognized that other opaque minerals may be included with the ilmenite.

Kyanite.—The colorless, rectangular, prismatic grains of kyanite show basal and pinacoidal cleavage. The average grain size is 0.08 mm. by 0.24 mm.

Leucoxene.—The leucoxene grains are white to brown and have a porous, earthy appearance. Most of the leucoxene is attached to ilmenite grains.

Pyrite.—Angular crystal fragments of cubic and pyritohedral forms are characteristic of this mineral.

Rutile.—The reddish-brown elongated prismatic crystals generally show striations oblique to the prism edge and rarely contain inclusions.

Titanite.—The greenish-yellow, clear, euhedral grains of titanite contain only occasional needle-like inclusions.

Tourmaline.—The color ranges from brown to green and blue. The grains are generally prismatic crystals, but some rounded forms are present. It is thought that the rounded grains may be detrital tourmaline which remained cemented to quartz grains during the preparation of the sample, and were freed through crushing. Opaque and colorless inclusions are not uncommon.

Zircon.—Zircon occurs dominantly as rather cloudy, elliptical, zoned grains which do not have definite prismatic or pyramidal forms. Clear, prismatic crystals with pyramidal terminations, which may or may not be zoned, are also present. In some cases the central zones of a zoned zircon may be roughly elliptical in shape, whereas the succeeding zones show regular crystalline outlines with well developed angles between the prismatic and pyramidal faces. The zones of many of the zircons show rounded angles between the prismatic and pyramidal faces, and are rounded at the apex of the pyramid. Crystals were noted in which outer zones cut across inner zones in such a manner as to suggest that the crystal had suffered re-solution before the formation of the exterior zones. The grains range from colorless to light pink and contain small colorless and opaque, regular, irregular and acicular inclusions. The zircon ranges in size from 0.016 mm. to 0.16 mm., with the average size being about 0.08 mm.

Discussion of the Heavy Mineral Inclusion Suite.—In the St. Peter sandstone zircon and apatite dominate as inclusions, with biotite and hornblende rather important locally. Titanite, rutile, ilmenite, garnet, pyrite and tourmaline are present in kyanite and garnet in small quantities suggests that metamorphic rocks played a part in supplying material to the St. Peter sandstone. The three samples of Keweenawan sandstone from the Bayfield group contain an inclusion suite similar to the St. Peter

TABLE 10.—*Relative Percentages of Heavy Mineral Inclusions in Three Samples of Keweenawan Sandstone (A1, A2, and A3) and Sixteen Samples of St. Peter Sandstone*

Sample No.	Zircon	Tourmaline (Total)	Brown	Green	Blue	Apatite	Garnet	Fluorite	Biotite	Titanite	Hornblende	Kyanite	Rutile	Leucoxene	Ilmenite	Pyrite
A1	33	X	X		X	2	1	X	1	1	X		X	11	51	P
A2	52					2	X	X	2	3	3		X		38	P
A3	32	X	X			1			X	1	X		X		66	P
4M	58	X	X		X	21	1	X	9	3	4	X	X		4	P
9M	53	2	2			16	1		9	5	6			X	8	P
32M	50	X	X			24	1		15	2	5	X	X		3	P
2E	69	X	X			13	2		7	4	1	2	X		2	C
20E	81	X	X	X		10	1		4	1	X		X		3	P
7L	74	1	1		X	7	1	X	6	4	2		2		3	C
12N	72	1	1			17	X		3	X	4		1		2	P
9P	72	1	1		X	15			6	2	4		X		X	P
8S	54	1	1			20	1		11	1	6		X		6	P
26S	53	2	2	X		29	1		6	1	4		X	2	2	P
3Y	62	X	X			14	X		2	1	3		1		17	P
5K	29	1	1			15	1		31	4	18		X		1	P
6Z	44	1	1			7	1		4	5	34		X		4	P
7C	70	X	X			10	1		3	3	6		1	X	6	
10A	54					20	2		3	4	7	1	1		8	P
2B	65					13	1		5	4	9		X	X	3	P

almost all samples, whereas fluorite, kyanite and leucoxene are more rarely present. The abundance of zircon and apatite suggests that a large part of the quartz grains were derived from a terrane consisting of acid to intermediate plutonic rocks.

The pyrite, ilmenite, titanite, hornblende, biotite, fluorite and tourmaline may well have been derived from the same source. The presence of the main difference being that ilmenite is more abundant in the former.

A comparison of the detrital heavy mineral suite with the inclusion suite indicates that titanite, hornblende, kyanite, biotite, fluorite and a large part of the apatite had been eliminated prior to the deposition of the sandstone. Also garnet and rutile appear to be more common in the inclusion suite, whereas tourmaline

in less common. The rareness of tourmaline in the inclusion suite may be related to the original size of the tourmaline crystals or to their time of crystallization within the parent igneous rock.

The successful isolation of the inclusion suite by the above method indicates that inclusions within the original quartz grains of a quartzite would be likewise freed during the usual grinding procedure and become intermixed with the detrital suite. In case the detrital suite is well rounded, most of the inclusion minerals may be identified by their crystal form; if the detrital suite is little rounded, trouble may be encountered. The following minerals are present as well developed crystals within the quartz grains of the St. Peter sandstone: apatite, tourmaline, garnet, hornblende, rutile, pyrite and titanite. Fluorite, biotite, ilmenite, kyanite, leucoxene and in some cases hornblende are present as irregular grains, whereas zircon may occur as well defined crystals with sharply defined angles between adjacent faces, or very commonly as rather elliptical grains. This latter type of grain has the same appearance both in the inclusion and detrital suites of the St. Peter sandstone. It is to be noted that elliptical or rather rounded zircon is found in some igneous rocks (29).

The failure to recognize that inclusion minerals may enter the detrital suite during crushing may lead to erroneous conclusions regarding the distance the material has been transported. Holmes (30) states that, "Accessory minerals, such as zircon, may be represented in a sand by both well-rounded and sharply angular (idiomorphic) samples, the reason being that these minerals, occurring as inclusions in larger grains, may be protected from friction during part of, or throughout, their journey." This possiblity should be considered for such a situation might lead to the conclusion that some of the heavy detritals were derived from a local source.

Comparison of the Wisconsin St. Peter Suite with the Suites of the Cambrian Sandstones of Wisconsin.—Table 11 shows the average per cent of the critical heavy minerals of the St. Peter sandstone as compared with the Madison, Jordan, Franconia, Galesville, Eau Claire and Mt. Simon sandstones of Upper Cambrian age.

The sandstones listed in Table 11 may be divided into four groups on the basis of their heavy mineral suites

1. Mt. Simon—dominant ilmenite and leucoxene, with zircon and tourmaline common and garnet rare.
2. St. Peter, Madison and Galesville—Zircon dominant with tourmaline, leucoxene and ilmenite common, and garnet rare.
3. Franconia and Jordan—Garnet dominant with tourmaline and zircon rather common.
4. Eau Claire—zircon, garnet, ilmenite and leucoxene common to abundant with tourmaline rather rare.

In groups 1, 2 and 3 the titanium

TABLE 11.—*Comparison of the Heavy Minerals of the St. Peter Sandstone with the Upper Cambrian Sandstones of Wisconsin*

	St. Peter	Madison (31)	Jordan (32)	Franconia (33)	Galesville (34)	Eau Claire (31)	Mt. Simon (31)
Zircon	61	64	10–25	4	25–50	29	18
Tourmaline	15	17	5–10	15	10–25	4	10
Garnet	X	2	75–100	80	0–10	22	2
Ilmenite	5	X	X	X	5–10	30	50
Leucoxene	16	11	X	X	1–5	11	21
Anatase	1	3		X	X	2	X
Ceylonite	X				X		
Apatite	X			X			X
Rutile	X	2		X		1	X
Staurolite	X					X	X

minerals, zircon, and garnet respectively are the dominant minerals, while group 4 appears to be a combination of the first three types. It should be possible to distinguish without great difficulty, on the basis of heavy minerals, to which of the four groups a particular sandstone belongs; however, identification of a sandstone within a group is not simple. At present it is impossible to distinguish either the St. Peter from the Madison and Galesville, or that part of the St. Peter which is characterized by a dominance of leucoxene and ilmenite from the Mt. Simon.

Comparison of the Wisconsin St. Peter with That of the Mississippi Valley.—Table 12 clearly shows that the heavy minerals of the St. Peter sandstone are remarkably similar over very large areas. The fact that some of the minerals, which occur in relatively small percentages, have not been reported from all the localities studied, may be due to mistaken

TABLE 12.—*General Distribution of Heavy Minerals in the St. Peter Sandstone According to Various Authors*

	No. of Samples	Tourmaline	Zircon	Garnet	Ceylonite	Anatase	Apatite	Rutile	Staurolite	Leucoxene	Ilmenite	Hornblende	Monazite
Wisconsin—Tyler	281	C	D	X	X	R	X	X	X	C	P		
Kansas —Edson	233	D	D	X		X							X
Minnesota—Thiel	103	A	A	X	X			C		C		X	X
Illinois —Lamar	15	A	D	X	X		P						
Arkansas —Giles	7	F	D			P	P	P		P			
Iowa —Thiel	3	C	F					R		X			
Missouri —Cordry	3	D	D			X				X			
Arkansas —Edson	2	D	A					X					
Missouri —Edson	2	D	A		R	X						R	
Minnesota—Edson	1	A	A	R					R		C?		

identity as well as absence of some minerals from certain areas. Leucoxene, ilmenite, apatite and ceylonite in particular, probably are more common in their occurrence than Table 12 indicates. Zircon and tourmaline apparently are the two chief heavy minerals, with rutile, anatase, leucoxene, ilmenite, garnet, hornblende, ceylonite, monazite, apatite and staurolite common to rare.

This table, which is compiled from the published literature on the St. Peter, is intended to show only the general distribution of the various heavy minerals. See previous work on the heavy minerals for references.

Possible Sources of the St. Peter Sandstone.—Although the heavy mineral inclusion suite suggests that the St. Peter sands were originally derived from an acid to intermediate plutonic terrane, the presence of only the very stable minerals in the detrital suite indicates that the sands have probably passed through more than one cycle of erosion and deposition. Likewise the absence of the less stable inclusion minerals in the detrital suite suggests, that although these minerals were present at one time as detritals, they have since been eliminated. It appears likely then that the St. Peter sandstone was derived from pre-existing sediments, and therefore it is well to examine the possible sedimentary sources.

Cambrian Source.—The upper Cambrian sandstones may have furnished sands to the St. Peter, inasmuch as they were undergoing erosion during at least part of the time represented by the unconformity at the base of the St. Peter.

The Mt. Simon heavy mineral suite appears to be characterized by a dominance of titanium minerals, with zircon and tourmaline common, and garnet very rare. The St. Peter heavy mineral suite of south central Wisconsin is likewise characterized by a dominance of titanium minerals, with zircon and tourmaline common and garnet rare. Thus on the basis of heavy minerals, as well as grain size and availability of the sands, the Mt. Simon sandstone may be considered a very likely source for the St. Peter of south-Central Wisconsin.

The Eau Claire sandstone of Wisconsin apparently contains garnet as a common constituent of the heavy mineral suite and thus appears to be a less likely source for the St. Peter sands.

The heavy mineral suite of the Galesville in central Wisconsin appears to be identical with that of the St. Peter sandstone. It is unlikely, however, that the St. Peter was derived from the Galesville, unless the Galesville was exposed over wide areas with the Franconia and Jordan removed. It is more probable that the St. Peter and the Galesville of central Wisconsin were derived from the same source.

The rareness of garnet in the St. Peter at Oconomowoc, where it rests upon the Franconia, indicates that the St. Peter was not deriving its sands from the underlying formation at this locality. It is more probable that the sands derived from the Franconia and Jordan during the

TABLE 13.—*Keweenawan Sandstones and Arkoses*

Sample No.	Tourmaline (Total)	Brown	Green	Blue	Colorless	Zircon (total)	Colorless	Pink	Garnet (Colorless)	Pink	Anatase	Apatite	Rutile	Leucoxene	Ilmenite	Epidote (altered)	Clear	*Zoisite*	Formation
11036	X	X	X	X		7	7	X	X				X	10	83				Chequamegon ss.
11019A	X	X	X	X		6	6					X	X	6	88				"
10000A	1	1				6	6					2	X	5	86				"
11053	15	13	2	X	X	52	52	X						31	2				Devils Island ss.
11057	17	14	3			59	59	X	X				X	23	1				"
11089	3	2	1	X	X	90	90	X	X		Xb	1	1	4	1				"
11189	1	1	X	X		6	6						X	7	86				Orienta ss.
10001A	X	X				8	8					5		5	82				"
10002A	1	1				6	6					2		5	86				"
11160	X	X				1	1		7					2	37	44	7	2	Oronto (Freda ss.)
11061	X	X				1	1		9					2	3	81	4	X	"
11161	X	X				2	2		9				X	1	17	66	3	2	" (Outer Congl.)
14668	X	X				42	42	X			1		1	6	50				Barron quartzite
14681	X		X			36	36				3			28	33				"
17376	2	1	1			81	80	1					1	15	1				Hinckley ss.

pre-St. Peter erosion interval were deposited farther to the south and have no equivalent in this region. The absence or extreme rareness of garnet in the St. Peter sandstone also suggests that the Franconia and Jordan formations of Wisconsin could not have been the source for the St. Peter sands.

Pre-Cambrian Source.—Inasmuch as the Laurentian Shield has served as a positive land mass throughout much of geologic time, it is to be expected that the pre-Cambrian sediments associated with it may have served as a source for the later Paleozoic sandstones. The lack of published, detailed, heavy mineral data, suggested a study of the samples listed in Table 13 in order to determine what might be expected in some of the older sedimentary rocks of the Lake Superior region.

The sediments of the Middle Keweenawan are dominantly sandstones and conglomerates which are interbedded with lava flows (35). The particles of sand are composed largely of fragments of acid igneous rocks and form a possible but unlikely source for the St. Peter sandstone.

The upper Keweenawan sandstones and arkoses have been divided into the Oronto and Bayfield groups by Thwaites (36).

The Oronto group consists of the following formations in ascending order: Outer conglomerate, Nonesuch shale, Freda sandstone, Eileen sandstone, and Amnicon shales, sandstones and conglomerates. The total thickness of the Oronto group is about 21,000 feet. Table 13 lists the heavy minerals present and the relative per cent, in two samples of the Freda sandstone, and one sample of the Outer Conglomerate. The Oronto group appears to be characterized by a high percentage of epidote and ilmenite, with garnet more abundant than zircon and tourmaline. The felspathic nature of the Oronto group plus the dominance of garnet over zircon and tourmaline makes this group an unlikely source for the St. Peter sandstone.

The Bayfield group consists of about 4,300 feet of sediments, which have been subdivided, from the base upward, into the Orienta, Devil's Island and Chequamegon sandstones. Table 13 indicates that the heavy mineral suites of the Chequamegon and Orienta sandstones are very similar; they contain a high percentage of ilmenite with lesser amounts of leucoxene, zircon and tourmaline. The Devil's Island, a clean quartz sandstone, is characterized by the dominance of zircon with common leucoxene and tourmaline. The heavy mineral suite of the Devil's Island sandstone contains the same minerals, in approximately the same ratio, as the St. Peter, however, there is one apparent difference which precludes the possibility that the Devil's Island sandstone might have been the sole source of the St. Peter. This is the presence of an appreciable percentage of pink zircon in the St. Peter, with extreme rarity of this variety in the Devil's Island sandstone. It is of course possible that the Devil's Island sandstone served as a partial source for the St. Peter, and that the

pink zircon suite was introduced from elsewhere.

The Chequamegon and Orienta sandstones contain locally a large per cent by weight of ilmenite, which taken together with leucoxene in sample No. 11036 comprises 27.5 per cent (by weight) of the total sample and 94.3 per cent (by weight) of the heavy fraction. If part of the ilmenite were lost through alteration and transportation, the heavy mineral suite derived from the Chequamegon and Orienta sandstones would be very similar to that of the St. Peter, Galesville and Mt. Simon sandstones of Wisconsin, with the exception again that the Keweenawan sandstones lack the pink zircon.

The samples of Hinckley sandstone and Barron quartzite studied have the same general heavy mineral suite as the St. Peter sandstone, but they too are lacking in pink zircon and thus could not have been the sole source of the St. Peter.

The pink variety of zircon is a common constituent of the Huronian quartzites of northern Wisconsin and Michigan (37). These rocks contain essentially the same heavy mineral suite as the St. Peter sandstone. It is entirely possible, therefore, that the Huronian sediments, either directly or indirectly furnished sands to the St. Peter.

SUMMARY AND CONCLUSIONS

1. Zircon, tourmaline, leucoxene and ilmenite compose 97 per cent or more of the detrital heavy minerals of the St. Peter sandstone, with anatase, ceylonite, apatite, rutile, staurolite and garnet constituting the other 3 per cent. The minerals pyrite, celestite, jarosite and dahllite are present in variable amounts, in some cases flooding the samples.

2. Quartz is the chief light mineral, generally comprising over 97 per cent of the sandstone. Authigenic and detrital feldspars are common, but are not particularly abundant. Glauconite is present in the Glenwood horizon.

3. Jarosite, although present in the St. Peter sandstone, is particularly abundant in the Glenwood horizon.

4. The heavy mineral suite of the St. Peter sandstone is remarkably uniform throughout the Mississippi valley; however, there is a pronounced concentration of leucoxene and ilmenite in south central Wisconsin.

5. It is not possible at present to distinguish the Galesville from the St. Peter on the basis of heavy minerals, but it is possible to distinguish the St. Peter from the Franconia and Jordan sandstones of Wisconsin.

6. The limited variety and great stability of the allothogenic, heavy minerals suggests a sedimentary terrane as the immediate source of the St. Peter sandstone.

7. The Jordan and Franconia sandstone and the Oronto arkose supplied little if any material to the St. Peter. The Bayfield and Hinckley sandstones and the Barron quartzite may have furnished sands to the St. Peter, whereas it is probable that the Mt. Simon sandstone and the Huronian quartzites served either as a partial or entire source.

8. The application of Mackie's general inclusion law to the St. Peter suggests that the quartz was largely, ultimately, derived from a granitic terrane.

9. The regular inclusions recovered from the quartz grains by means of a new procedure were found to consist principally of zircon and apatite, with biotite and hornblende important locally. Titanite, rutile, ilmenite, garnet, pyrite and tourmaline are present in almost all the samples examined, whereas fluorite, kyanite and leucoxene are more rarely present.

10. Minerals that are susceptible to elimination by the processes of weathering and erosion may occur as inclusions within quartz grains. These less stable minerals which may not be present in the detrital suite, are characteristic of the original igneous source rock and thus help to solve the problem of determining the provenance of the sediment. A study of the inclusion suite as compared with the detrital suite of the St. Peter sandstone indicates that titanite, hornblende, kyanite, biotite, fluorite and most of the apatite have been largely, if not wholly, eliminated during the history of the sand.

11. The inclusion suite of the St. Peter sandstone indicates that the sands were ultimately, largely derived from a granitic area with minor contributions from a metamorphic terrane.

12. If sand grains are crushed during the preparation of a sample, inclusions may become freed and enter the detrital suite. This situation may lead to the erroneous conclusion that, since the grains do not show the effects of long transportation, they must have been derived from a local source.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 6, NO. 2, PP. 85–96, FIGS. 1–5, TABLES 1–10, AUGUST, 1936

AN ANALYSIS OF THE SHAPES OF GLACIAL COBBLES

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ABSTRACT

Counts of 626 cobbles from Wisconsin till collected at random showed that not over 3 to 4 per cent of the cobbles show prominent glacial striation or shaping, these characteristics being about ten times as abundant among the limestone cobbles as among the other sedimentary, metamorphic, and igneous rocks. Detailed measurements and evaluation of shapes and markings were made on 300 selected glacial cobbles. These showed a dominance of tabular forms with a tendency toward pointed pentagonal profiles and practically all these were smoothed and rounded on the edges. The dominant striation pattern is a subparallel one which is almost universally parallel to the long axis of the cobble.

INTRODUCTION

The following study of glacial cobble shapes was made as a part of the writer's inquiry as to the comparative shapes and markings of cobbles modified by glaciers and by ice jams in Artic and sub-Artic rivers. The work of valley glaciers and ice jams was studied in Alaska and Yukon Territory in 1931 and in the summer of 1933 two weeks of field work were devoted to the observations and measurements on cobbles shaped by continental glacier ice which are reported below.[1] The general comparative conclusions are best presented after the specific findings have been stated and for this reason the following analysis of the shapes of glacier cobbles is presented first, to be followed by a report on the Alaskan and Yukon observations and the general conclusions.

The cobbles here described were all collected from the Wisconsin terminal moraine in the vicinity of Baraboo and Devil's Lake, Wisconsin. The chief purpose of these collections was to secure cobbles strongly and maturely modified by glacial abrasion, and previous experience in this region had indicated that there was an abundance of such material to be found. It is believed that the conclusions reached are valid for the cobbles of fresh Pleistocene tills in which limestone is predominant.[2] An effort was made throughout the field work to take observations and measurements according to a definite numerical or verbal schedule so that the degree of development of given qualities could be summarized numerically and would be amenable to statistical correlation if such were desirable.

[1] This study was aided by allotment from a grant made to Washington University by the Rockefeller Foundation for Research in Science.

[2] For simplicity, the term cobble is used throughout the paper, since only about 10 per cent of the whole number were large enough to be classified as boulders in a strict sense.

ANALYSIS OF SHAPE CHARACTERISTICS

The principal shape studies were made on 300 selected cobbles. In order to indicate the position of these selected cobbles among all the pebbles and cobbles occurring in the till of the Baraboo region several random collections were classified, as shown in Tables 1 to 5.

Of the cobbles classified in Tables 1 to 4 (626 in number) 56 per cent were limestone, 17 per cent were siliceous rocks, quartzite, chert, or vein quartz, 12 per cent were other sedimentary rocks, and the remain-

TABLE 1.—*Group A, Devil's Lake, Wisconsin*
A random collection of 200 cobbles between 50 and 200 mm. in diameter from road cut in terminal moraine east of C. and N. W. R. R. tracks and north of crossing at north end of lake

Rock	Without striae or facets	Faint striae	Clear striae one side	Clear striae two sides or grid one side	Grid two sides	Grid several sides	Total No. of cobbles
Red quartzite	4	4	—	—	—	—	8
White quartzite	1	2	—	—	—	—	3
Vein quartz	1	—	—	—	—	—	1
Jasper conglomerate	—	1	—	—	—	—	1
Cambrian quartzite conglomerate	1	1	—	—	—	—	2
Sandstone	5	1	1	—	—	—	7
	1				1		
Greywacke (Quartzose)	—	4	—	—	—	—	6
Red granite	1	—	—	—	—	—	1
Diorite and Diabase	4	10	4	1	—	—	19
Slate, greenstone	—	2	—	1	—	—	3
Limestone	14	50	43	31	9	2	149
Totals	32	75	48	33	10	2	200

TABLE 2.—*Group B, Baraboo, Wisconsin*
A random collection of 136 cobbles from road cut at the terminal moraine, Highway No. 12, north of Baraboo.

Rock	Without striae or facets	Faint striae	Clear striae one side	Clear striae two sides or grid one side	Grid two sides	Grid several sides	Total No. of cobbles
Quartzite	32	4	—	—	—	—	36
Vein quartz	2	—	—	—	—	—	2
Chert	5	—	—	—	—	—	5
Cambrian quartzite conglomerate	12	—	—	—	—	—	12
Sandstone	34	3	—	—	—	—	37
Diorite	1	1	—	—	—	—	2
Greenstone	—	2	—	—	—	—	2
Rhyolite	4	1	—	—	—	—	5
Limestone	13	18	4	—	—	—	35
Totals	103	29	4	0	0	0	136

TABLE 3.—*Group C, Baraboo, Wisconsin*
A second random collection of 137 cobbles from road cut at the terminal moraine, Highway No. 12, north of Baraboo.

Rock	Without striae or facets	Faint striae	Clear striae one side	Clear striae two sides or grid one side	Grid two sides	Grid several sides	Total No. of cobbles
Quartzite	24	2	—	—	—	—	26
Vein quartz	1	—	2	—	—	—	3
Chert	4	1	1	—	—	—	6
Sandstone	19	3	—	—	—	—	22
Red shale	1	—	2	—	—	—	3
Granite	5	—	—	—	—	—	5
Diorite and gabbro	2	1	1	—	—	—	4
Greenstone	—	1	2	—	—	—	3
Rhyolite	5	2	—	—	—	—	7
Limestone	4	20	24	8	2	—	58
Totals	65	30	32	8	2	—	137

TABLE 4.—*Group D, Baraboo, Wisconsin*
A third random collection of 153 cobbles from road cut at the terminal moraine, Highway No. 12, north of Baraboo.

Rock	Without striae or facets	Faint striae	Clear striae one side	Clear striae two sides or grid one side	Grid two sides	Grid several sides	Total No. of cobbles
Chert vein quartz	2	—	—	—	—	—	2
Sandstone	4	—	—	—	—	—	4
Granite	8	5	—	—	—	—	13
Diorite and gabbro	5	9	1	—	—	—	15
Greenstone	—	—	7	—	—	—	7
Rhyolite	2	—	—	—	—	—	2
Limestone	24	41	34	9	2	—	110
Totals	45	55	42	9	2	—	153

TABLE 5.—*Summary of Groups A, B, C and D*

Rock	Without striae or facets	Faint striae	Clear striae one side	Clear striae two sides or grid one side	Grid two sides	Grid several sides	Total No. of cobbles
All other rocks	188	60	21	2	1	0	272
Limestone	57	129	105	48	13	2	354
Totals	245	189	126	50	14	2	626

ing 15 per cent were igneous rocks. It was found that various exposures of till, separated by distances of a half mile or less, showed an appreciable difference in the details of lithologic composition, as shown by close inspection of the tables, though the general facts are consistent. 40 per cent of the whole series showed no striae or facets and 50 per cent more were limited either to faint striae or to clear striae on one side only. All the conspicuously modified cobbles of the last three groups of the tables amount to only 10 per cent of the whole. These and

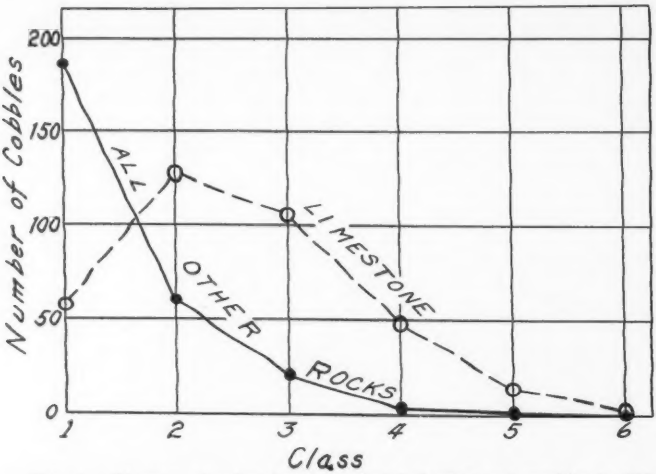

FIG. 1.—Diagram showing degree of glacial shaping and marking in 626 pebbles and cobbles taken at random from Wisconsin drift near Baraboo. Class designations are as follows: 1, No striae or facets; 2, faint straie; 3, clear striae one side; 4, clear striae two sides or grid one side; 5, grid two sides; 6, grid several sides, ideal. The contrast between the limestone, the majority of cobbles of which are at least recognizably striated, and the remaining rocks, the cobbles of which are preponderantly lacking in glacial marks, is well shown.

The siliceous cobbles, for the most part, were not striated or faceted at all; a minority showed faint striae or very limited areas of clear striations. Other sedimentary rocks, or igneous rocks, especially if fine-grained, showed slightly more tendency to be faceted or striated, but all these were much inferior to the limestone in the proportion and prominence of glacial markings. About other details are shown in Table 5 and Figure 1.

Several schedules of observations were tried in analyzing the shapes of distinctive glacial cobbles before a fairly satisfactory one was developed. This is shown in Table 6.

Three hundred cobbles were analyzed according to the scheme of Table 6. Of these, 44 were selected from Group A, as tabulated in Table

TABLE 6.—*Schedule used for Analysis of Shapes and Markings of Glacial Cobbles*

Serial Number of Cobble
D_a (Major diameter)
D_b (Intermediate diameter)
D_c (Minor diameter)
Kind of Rock
General Shape:
Parallel tabular
Wedge tabular
Semitabular
Subtabular
Roof shaped
Wedge shaped
Single lens
Double lens
Pyramidal
Bipyramidal
Prismoidal
Nodular
Form of Margin (usually as viewed from top)
Parallel-sided
Triangular
Circular
Polygonal
Reniform
Lenticular
Pentagonal
Hexagonal
Septagonal
Rectangular
Trapezoidal
Quadrangular
Bi-lenticular
Oval
Rhombic

Surface Features
Margin (Well-rounded = 1)
(Moderately-rounded = 2)
(Broken, rough = 3)
Spall scars (Marked = 1)
(Present = 2)
(Faint = 3)
Etch scars (Marked = 1)
(Present = 2)
(Faint = 3)
Snub scars (Marked = 1)
(Present = 2)
(Faint = 3)
Flatness of facet (Longitudinal)
(Transverse)
Edge Features
Facet edges (Well-rounded = 1)
(Moderately-rounded = 2)
(One edge snubbed)
(One end snubbed)
(Two ends snubbed)
Striae
Per cent of surface
Parallel pattern
Subparallel
Scattered
Grid
Moulded
Parallel to major axis

Explanation of usage.

The general shape refers to the primary form; the form of margin to the profile in a plane normal to the short axis, that is, as seen from above when lying on a table. In the case of most of the general shape terms this application holds, but with some, such as *prismoidal*, followed by *quadrangular*, a prism of quadrangular section would be understood.

If tabularity fails by curvature it is described as semitabularity, if by reduced area of parallel faces it is called subtabularity, if by lack of parallelism of faces, it is wedge-tabularity. *Spall* scars are the marks of major breaks not evidently due to the pushings or snubbing effect of ice pressure. Etch scars are the pits, enlarged joints, and crumbled parts of the surface due to solution. *Snub* scars are the plucked breaks found usually at the lee ends of glacially abraded surfaces. The subparallel pattern differs from the parallel pattern in consisting of slightly divergent, spray-like striae, rather than a rigidly parallel system. The *moulded pattern* is a subparallel one in which striae carry over the edges and around the convexities in a form-line configuration.

1, and collected from the terminal moraine north of Devil's Lake. In addition, 156 more cobbles were selected from the same till outcrop. The remaining 100 were selected from the excavation in the terminal moraine south of Steinke's Flat, east of Devil's Lake and from an excavation east of Sauk City.

Two hundred and ninety of the cobbles were limestone, seven of the remainder being diorite, and one each greenstone, slate and quartzite. This selection, on the basis of marked striation and shaping, further confirms the prominence of limestone

shown in Tables 1 to 5. Sizes varied from 5 cm. to 100 cm. diameters. Cobbles whose major diameter was under 10 cm. numbered 64, those

As indicated in the schedule, the major, intermediate and minor axes of each cobble were measured in centimeters.[4] The general proportions of the cobbles are shown by the tables and outlines of Figure 2. It is seen from these that the most common form is that of a slab having a length about 1.4 times its width and about 2.25 times its thickness. A few are over 4 times as long as they are thick and over twice as long as wide.

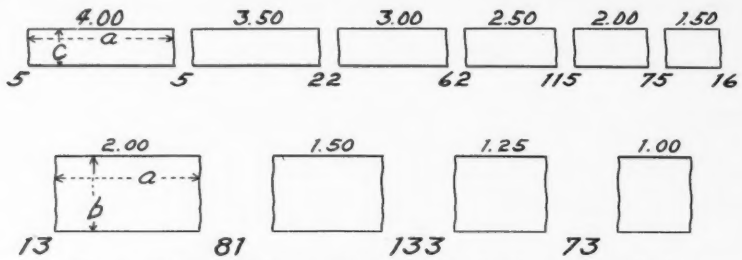

FIG. 2.—Diagram showing numbers of cobbles having various ratios between length (a) and thickness (c), in the upper row of rectangles, and between length (a) and width (b) in the lower row. The modal ratio of length to thickness is between 2. and 2.50, and of length to width is between 1.25 and 1.50. the modal shape would thus be shown by a cobble 10 cm. long, about 4.5 cm. thick, and about 7 cm. wide.

from 10 to 19 cm. 175, those from 20 to 29 cm. 31, from 30 to 39 cm. 15, from 40 to 49 cm. 7, 50 to 59 cm. 4, 60 to 69 cm. 1, 70 to 79 cm. 2, 80 to 89 cm. 0, 90 to 99 cm. 0, and 100 cm. and above 1.

TABLE 7.—*General Shapes of 300 Glacial Cobbles*

Shape Classification	Number
Parallel Tabular	98
Wedge Tabular	47
Semitabular	29.5[3]
Subtabular	2.5
Roof-Shaped	27.5
Wedge-Shaped	10
Single Lens	4
Double Lens	10
Pyramid	10
Double Pyramid	7
Prism	41
Nodular	12.5
Ellipsoid	1
Total	300

[3] In several instances cobbles were classified as intermediate between two types and were assigned half to each; this accounts for the fractions

The general shape classification of the cobbles is shown in Table 7.

It is clear from the data recorded in Table 7 that the predominant form of the glacial cobbles is tabular. About one-third are parallel tabular, and another third is composed of forms like wedge-tabular, semitabular and lens-shaped, which are akin

[4] The longest or major diameter was first measured, after which the longest and shortest diameters normal to it are measured as the intermediate and minor diameters. In practice, the two latter are measured to the sides of an imaginary enveloping right parallelopiped, where protruding points are not quite on lines normal to the major axis. A rule is used rather than a caliper.

to the parallel tabular form. Quite clearly this is due initially to the breaking of the limestone into slabs with nearly parallel faces, but is also due in the finished glacial cobble to the greater susceptibility of this initial form to sustained abrasion and rubbing on the two opposed, principal faces. The form of these limestone glacial cobbles is due equally to the inherent structure of the rock and to the opportunity which this rock affords for the development of a characteristic and mature ice-abraded shape.

The classification of marginal shapes is shown in Table 8. About 85 per cent of the cobbles were assigned to pure types and the remainder as hybrid between two of these. The most abundant pure type was pentagonal, the margin showing a frontal point at the intersection of two sides. Behind these were two other sides, and a plucked or snubbed rear end made up the fifth line of the perimeter. Next came quadrangular and triangular margins, in order, followed by polygonal and other forms as shown in the table. Among the more abundant mixed types, of the 19 listed under pentagonal 8 were also partially reniform or kidney-shaped, 4 partially triangular. Of the 17 partially reniform, in addition to the 8 mentioned, 5 were partially polygonal and 4 partially triangular. Of the 13 partially triangular, in addition to the linkages mentioned, 5 were partially oval.

It is evident, therefore, that about two-thirds of the margins might be described as pentagonal, quadrangular, triangular, polygonal, trapezoidal, or reniform. The remainder are scattered among the other nine types listed. The most characteristic shape, general and marginal, therefore, is seen to be parallel tabular, with a pentagonal margin, counting mixed types at half value, amounting in all to about 75 cobbles. Enough other cobbles partake of certain similarities to this type to impart strong support to it as a modal tendency. In 1930 von Engeln published a paper in which he described the typical glacial cobble as "flatiron-shaped" (1) The present writer was somewhat skeptical at the time of this dictum; first, on the ground that it was a judgment not supported by measurements or methods of analysis permitting ready verification by others, and second, as to its essential correctness. The present paper attempts in some degree to meet the first deficiency and, at the same

TABLE 8.—*Marginal Profiles of 300 Glacial Cobbles*

Type of margin	Pure	Mixed
Parallel-sided	5	4
Circular	2	6
Reniform	11	17
Lenticular	15	0
Bi-lenticular	6	0
Oval	14	11
Triangular	34	13
Rectangular	12	1
Quadrangular	36	4
Rhombic	1	0
Trapezoidal	15	1
Pentagonal	66	16
Hexagonal	14	3
Heptagonal	8	1
Polygonal	19	7
Total	258	(84)
	42=1/2	
	300	

time, in the finding of very numerous pentagonal forms, affords a striking vindication of von Engeln's recognition of "flatiron shapes." There are various forms of flatirons, as also of the pentagonal glacial cobbles, but it is a pleasure to grant that comparison to the shape of a flat-iron is as good a vernacular description as can readily be formulated[5] (Figures 3 and 4).

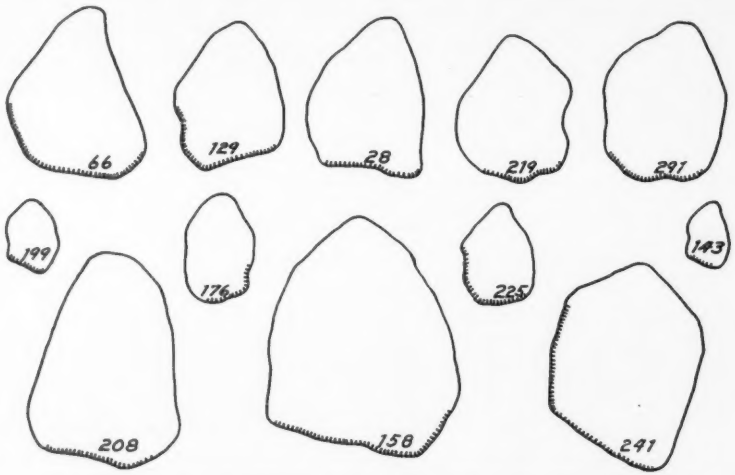

FIG. 3.—Profiles of pentagonal, and other "flatiron-shaped" cobbles. The largest of these cobbles are about 18 cm. long. All were arranged so that the stoss end is at the top in the cut. Portions of the margin showing recognizable snub scars are indicated by the hachures. The cobbles shown were somewhat selected but at least 40 or 50 comparable ones could have been picked from the 300.

The form of the margin is classified under the heading Surface Features in Table 6 as well-rounded, moderately rounded, or broken and rough. These distinctions refer to the margin as seen when looking down on the broadest face, and not to the edges which represent the junction of the broadest face with other faces. There are 128 well-rounded margins, 116 moderately-rounded margins and 56 which are rough and broken. It appears, therefore, that by far the majority of the cobbles showed definite evidence of at least superficial shaping of the margins by abrasion. Though the heading Spall Scars was carried in the schedule throughout the study, no scars were seen which the writer considered to be recognizable remnants of breaking or spalling of the blocks

[5] Certain additional details of von Engeln's description are not confirmed by the present study. In particular the Wisconsin "flatirons" appear to be crude, general types which could be used either side up and do not show the strongly marked bottom side, nor the humped upper side, mentioned by von Engeln.

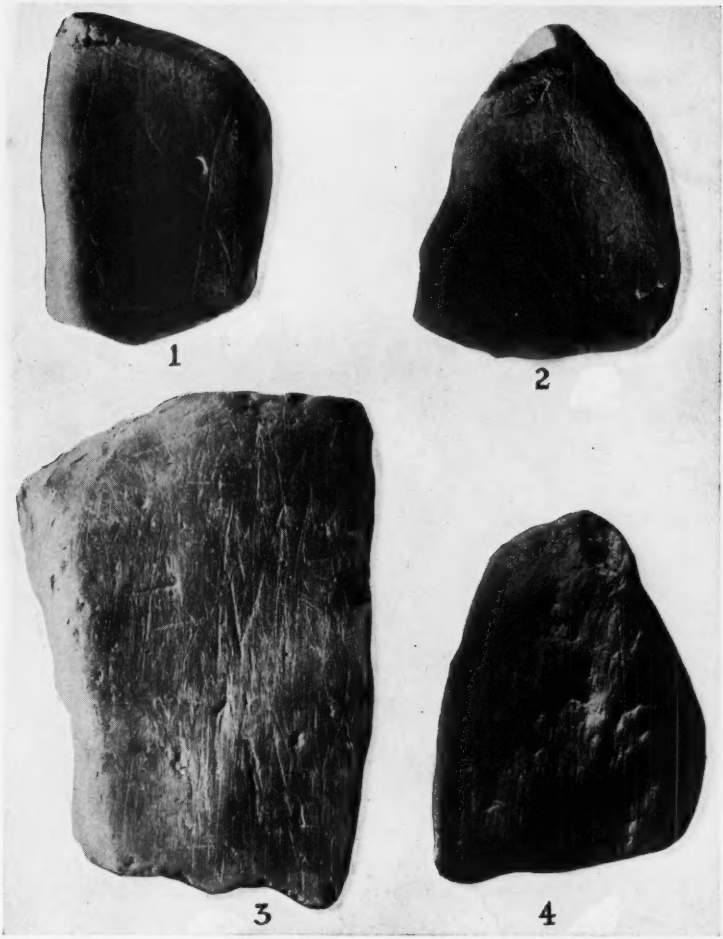

FIG. 4.—Representative glacial cobbles. Cobbles 1 and 3 may be described as parallel tabular, with trapezoidal margins. Cobbles 2 and 4 show pentagonal margins and 4 is somewhat pyramidal. Cobble 4 shows a moulded as well as subparallel striation pattern. Cobble 3 is dominantly subparallel, cobble 1 is subparallel and scatter patterned to almost equal degree, whereas cobble 2 shows a dominant scatter pattern. All show evidence of snubbing, though not with equal clarity in the photographs, at the lower end.

prior to the glacial action. This is in part due, of course, to the initial selection of well-marked glacial forms, but is nevertheless striking in showing how dominantly and maturely abraded the cobbles were.

Etch scars, due to solution around joints, with attendant crumbling, were recorded as present on 31 cobbles out of 300, thus only slightly over 10 per cent. No well-marked examples were seen. The characteristic push-off ends and edges of cobbles, here called snub scars due to the pressure flaking of fragments off their lee ends, were strongly marked on 43 cobbles, clearly present on 107, and faint or obscure on 42. They were not recorded at all on 108 cobbles. They are sufficiently abundant to be regarded as a characteristic feature of glacial cobbles, though not universally present.

TABLE 9.—*Distribution of Flatness Indexes*

	Longitudinal	Transverse
Mean	34.88	27.98
Mode	21	19
First Quartile	18.5	13
Median (2nd Quartile)	29.1	22.9
Third Quartile	45.5	35.8

A special effort was made to determine the variations of flatness of facets, both longitudinal and transverse. A simple method was used but it is believed that the general range of flatness has been determined fairly accurately. A straightedge was applied to the flattest facet on each cobble, and the middle ordinate of the curve by which it bulged from end to end or side to side was estimated by inspection. The quotient obtained by dividing this middle ordinate into the whole length, or width, of the facet, was recorded as an index of flatness. Thus an index of 20 on a facet of 80 mm. in length would imply a bulge or convexity of 4 mm., the facet being only moderately flat. An index of 100 would signify a convexity of only 1 mm. in 100 mm. and is a rather exceptional flatness.

The general distribution of longitudinal and transverse flatness indices is shown in Table 9. The average transverse flatness was slightly less the average longitudinal flatness and there were also a few more high indices of flatness in the longitudinal than in the transverse. The chief characteristics of the distribution are also shown in the table.

Of the whole 300 cobbles, 170 were classified as having generally rounded edges of facets, of which 144 showed no other edge markings of the type considered. Among the remaining 156 were 95 cobbles having one edge snubbed, 94 having one end snubbed, and 36 having both ends snubbed, Therefore, we may say that about half showed no recent or fresh snub marks on the edges or ends and the other half were so marked. A slightly larger proportionate incidence of snub scars was determined among the surface features reported above.

In the estimate of percentage of surface marked by striae, only one cobble was rated at 100 per cent, and one at 10 per cent. Only 18 were estimated at 40 per cent or less, and

only 35 at 90 per cent or over. The remaining 247, or 82 per cent of the whole, were rather evenly distributed among the 50, 60, 70 and 80 per cent ratings of striated surface. The average of the whole series was 67.4 per cent of striated surface.

The general striation characteristics of the 300 cobbles are summarized in Table 10 (Figure 5). Strongly parallel patterns are evidently very rare; these were patterns approximating the lines on a ruled paper or the pattern of well-developed slicken sided surfaces. Subparallel patterns occurred at a rate of nearly 800 per 1,000 and a parallelism of pattern to the major axis was nearly as common. This is evidently the preponderant and modal type. Scatter patterns were less than half as numerous.

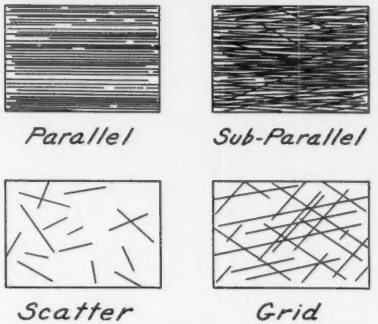

FIG. 5.—Diagram showing the four chief striation patterns distinguished. The parallel and subparallel patterns, though commonly showing more striations than the scatter and grid patterns, are not normally so strongly contrasted with the latter two as appears in the cut.

TABLE 10.—*Classification of Striation Characteristics*

	Parallel pattern	Sub-parallel pattern	Scatter pattern	Grid pattern	Moulded pattern	Pattern parallel to axis
Character strongly developed	0	211	45	2	28	189
Character partially developed	2	57	111	14	18	74
Index of occurrence per 1,000 cobbles[6]	3	791	335	30	123	753

SUMMARY

In summary, the following statements may be made:

(1) Even in a drift somewhat conspicuous for well-striated cobbles, the number of such is very small; in this case about 10 per cent of the limestone and scarcely over 1 per cent of all other rocks found in the Baraboo drift.

(2) In selecting well-shaped cobbles from the drift in which over half the cobbles were limestone, it is a corollary of (1), above that nearly all of the well-shaped 300 (Table 7 and 8) were limestone, only 10, or about 3 per cent being other rocks.

(3) There was a strong predominance of tabular forms with nearly parallel opposed faces, and the lengths and widths averaged about 2.3 and 1.4 times the thicknesses, respectively. It is believed that this shape is based on natural stratum-

[6] Counting partial development at one-half and strong development at one and transforming to rate per 1,000.

and-joint-controlled slabs of limestone, and that these in turn are adapted to remaining rather fixedly in the basal ice so as to acquire strongly characteristic glacial shapes and markings.

(4) There is a recognizable predominance of elongate shapes having a point forward and a nearly square end at the opposite extremity with a shape and surface marking developed by persistent movement in one direction. (See text on marginal profiles and surface features, and Figure 3.) This is the dominantly pentagonal form of this paper and the aptly described flatiron shape of von Engeln.

(5) The majority of the cobbles have rounded and smoothed edges. Only about 20 per cent were characterized by rough and broken edges. These edges are the rounded junctures of faces which are glacier-shaped and themselves are smoothed and somewhat striated.

(6) Snub scars, evidences of the pressure-spalling off of lee portions of the rock fragments were recognized on about two-thirds of them, and were very clear on at least half.

The orientation of rounded, stoss-facing and of plucked or spalled, lee-facing edges of pits in the cobble surfaces and of lee prismoids on the lee sides of resistant particles, as well as the rounded frontal points and snubbed lee margins in most cases, permitted confident determination of the last direction of motion. It is true that no completely independent criterion was available, but agreement among these several stoss and lee contrasts was considered conclusive.

(7) The longitudinal modal flatness of facets was represented by a middle ordinate one-twenty-first of the length of the facet, or roughly 5 units per 100; the transverse flatness is slightly less. A few cobbles have facets which are very much flatter.

(8) The average percentage of striated surface was 67.4 per cent.

(9) The preponderant striation pattern is subparallel and this is almost universally parallel to the long axis of the cobble. Scatter patterns are next in frequency and all others are comparatively rare.

REFERENCE

1. Von Engeln, O. D., Type form of faceted and striated glacial pebbles: *Am. Jour. Sci.*, (5), vol. 19, pp. 9–16, 1930.

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THE SHAPES OF GLACIAL AND ICE JAM COBBLES

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ABSTRACT

A total of 503 glacial cobbles and boulders in seven series were measured and classified as to type of rock, shape, character and degree of surface markings, and the like. One hundred and fifteen ice jam roundstones of various sizes were likewise measured and classified, in five different series. No absolute difference appears. The chief general distinction lies in the greater maturity of development of the stoss-snub surface on at least a few glacial dobbles, as compared with the slight modification of previous shape in ice jam cobbles. Grid patterns, crude bruises, and curved striae are more abundant, relatively, on ice jam cobbles and boulders than on those due to glaciation. On the basis of these criteria, the striated cobbles of southeastern river terraces are believed to be of ice jam origin.

INTRODUCTION

Propose of Study.—It has long been recognized that some rock fragments abraded by the movement of glacial ice are characterized by smoothed and striated facets. It has also been recognized that not all glacially-transported debris is so marked, that in some drift deposits pebbles showing such markings are relatively rare. Moreover, the distinctive shapes and striations are developed very strikingly on some kinds of rock, such as limestone or slate, and very imperfectly on many other kinds. General descriptions of glacial pebbles and boulders are found in nearly all elementary textbooks, but there have been few attempts to determine quantitatively what the distinctive glacial shape is.

Between 1919 and 1928, the writer found striated rocks of all sizes from pebbles to large boulders in various of the southeastern states and at a large number of river-terrace localities, which have been described in brief elsewhere (4). These have been thought not to be the product of glacial action, but as more likely due to the work of ice jams in rivers of the preiglacial region during the Pleistocene epochs of glacial expansion. That striated cobbles are produced in the ice jams of sub-arctic rivers has been known through the casual observations of geologists in Alaska, northern Canada and arctic Eurasia, but no detailed description of the process or of the cobbles themselves was extant at the time of the writer's earlier studies.

A comparative study of the cobbles and boulders striated by glaciers and ice jams in Alaska and Yukon Territory was made possible in 1931 by equal allotment from the Grants-in-Aid Committee of the National Research Council and the Rockefeller Fund to aid research in Science at Washington University. Fourteen weeks were spent in the field, including four weeks on the Yukon River between Whitehorse and Circle and ten weeks studying some fifteen glaciers of the Juneau, Copper River

and Seward regions. These studies have already been reported in part (1, 5, 7).

It had been planned, after studying the shapes and markings of cobbles abraded by ice jams and by glaciers in the Alaska-Yukon region, that a careful analysis be made of glacial cobbles from the drift of some part of the glaciated area in the United States, and finally a critical re-examination of the cobbles originally in question, from the river terraces of the southeastern United States. The field study of glacial cobbles was completed in June, 1933, in the Baraboo district of Wisconsin. (6) Re-examination of the southeastern cobbles in the near future is impossible because of transfer of the writer's residence and activities to the Hawaiian Islands for an indefinite period, and it appears best to report in full the studies made to date.

It was hoped that in making the several analyses of cobble shapes and markings distinctions could be drawn with sufficient definiteness to determine positively whether the southeastern cobbles are of ice-jam origin, and at the same time to develop criteria of value in the study of other faceted and striated rock fragments of obscure origin.

Method of Study.—In order to detach the study as far as possible from personal bias and to make the results as useful to others as possible, every effort was made in the study of a given group of cobbles to record their characteristics in numerical form, or to classify them with reference to a tabular scheme, so that a measure of the relative possession of certain features could be obtained. It is the writer's belief that wherever the study of objects not yet amenable to rigorous mathematical analysis can be approached by the method of recording presence or absence or degree of development of component elements, a long forward step has been made. Actual methods used in various instances will be apparent on examination of the data. In each case an attempt was made to secure essential information by the analysis of elements, adapting the particular procedure to the number and kinds of cobbles to be dealt with.

Acknowledgments.—Thanks are due to the Grants-in-Aid Committee of the National Research Council and to the committee in charge of the Rockefeller Fund for research in science at Washington University for allotments which made the field work in Alaska and the Yukon Territory possible. The assistance of various University and Research Council officials in arranging for the support of field studies is here gratefully acknowledged. Throughout the field work in Alaska, the writer was assisted by Louis L. Ray of St. Louis, whose intelligent suggestions in regard to methods and persevering attention to details have added substantially to the results of the study.

SHAPES OF GLACIAL COBBLES

Detailed Observations.—No place was found, in the course of the Alaskan studies, at which well-marked glacial cobbles or boulders are as abundant as they are in the drift of the Baraboo region, as described in the following paper (6). For this reason and the attendant variety in

character and markings of those scattered groups we were forced to study, no single unified scheme of observations comparable to that later elaborated in Wisconsin was used. It is believed, however, that the following notes on the several groups will be sufficiently clear.

Series No. 1, 100 specimens (Location 18)

Mendenhall Glacier at point on east lateral margin.
Terminal moraine till.

Group A, over 1 meter in diameter (25 specimens).

The largest block 6 by 5 by 4 meters; eight with at least one dimension over 2 meters. 80 per cent diorite; the remainder a hornblendic rock. Twelve showed strictly angular, unmodified corners; others showed slight rounding of edges, maximum to radius of 5 centimeters making index of 0.10[1] for roundness. All are blocks of essentially original shape; eleven have longest dimension at least twice the shortest. Fourteen are rough-edged and rough-surfaced, with reentrant fracture scars. Eleven are slightly rounded on corners or slightly smoothed on part of surface. No striations noted.

Group B, 256 mm. to 1,000 mm. (25 specimens).

Twenty are diorite, remainder are phyllite, schist, or gneiss. Three are sharply angular; index 0.00; five most rounded have indices of 0.27—0.22—0.18—0.12—0.10. Twenty-three showed no facets or striation; two slightly striated on crude facets.

Group C, 64 to 256 mm. (25 specimens).

Fourteen are diorite, remainder phyllite, gneiss and schist. Four are sharply angular, index 0.00; five most rounded range 0.50 to 0.29, remainder range downward. Only one showed faint striations.

[1] Roundness index $=r_1/R$, where r_1 is radius of curvature of sharpest edge and R is mean radius of the fragment, in the same units.

Group D, 8 to 64 mm. (25 specimens).

Seventeen are diorite, remainder phyllite, gneiss and schist. Two are angular, five most rounded range 0.35 to 0.20. No striations were recognized on any.

This series illustrates well how little distinctive glacial shaping and marking appears on much glacially-deposited debris. It occurs in a morainic accumulation which lay in front of and somewhat east of the ice margin of 1931 near the eastern lateral stream, where buried ice blocks were still melting under the unstable debris. The dimension classifications, proportions, and rounding indices are based on actual recorded measurements, omitted here in interest of brevity. Only three of the hundred showed striae and these were crude or faint.

Series No. 2, 25 specimens (Location 19)

Mendenhall Glacier, east lateral margin.
Debris deposited by sub-glacial ice.

This sample was found in an area 100 by 200 feet, and consisted of debris delivered probably by sub-glacial ice. The boulders and cobbles measured were estimated as about 5 per cent of the whole, and were selected as the most clearly and typically striated and shaped.

The three largest boulders were of 3 meters, 2 meters and 1 meter average diameter each. Eight others exceeded 25 cm. in diameter, seven were 12 to 25 cm., and seven under 12 cm. in diameter. About one-half were greenstone; the others gneiss, quartzite, diorite, etc. Nine were angular or subangular and several showed marked fracture reëntrants. Ten were glacially smoothed and moulded without drastic change of original shape and six were of water-rounded form. All were marked by short scratches or irregular gouges but only four showed strong systems of parallel striations. One had three well-cut, striated facets, two had two each and four more showed one

such facet. Depth of cutting of these facets was estimated at one-tenth of the length of facet in five instances and one-fifth in two instances.

A few of these boulders show striking and dominant glacial characteristics, the remainder are less completely marked. Fragments of the remaining 95 per cent of the whole deposit are preponderantly not marked at all by facets, striation, or distinctive glacial smoothing.

Series No. 3, 253 specimens (Location 37)

Super-glacial debris of medial moraine on Herbert Glacier.

Two hundred and ten specimens were unrounded, angular fragments of greenstone ranging from 3 to 25 cm. in diameter and showing no striations whatsoever. Thirty-six were angular and subangular diorite fragments of similar size and also without striae. Seven blocks of greenstone were found which showed faint, crude striations.

Series No. 4, 25 specimens (Locn 42)

Recessional moraine at Herbert Glacier.

These were selected specimens, estimated at 1 per cent or less, of whole. They range from 5 to 30 cm. in mean diameter. About three-fourths of these were black slate, the remainder being greenstone or phyllite. Most of the specimens were elongate prismoids parallel to the slaty cleavage with a length from two to four times the smallest dimension.

Facets were chiefly due to dressing of cleavage surfaces and most were striated parallel to length. A few showed broken, or slightly snubbed ends. The following are descriptions of typical specimens from the field notebook.

No. 2, 22 by 14 by 7 cm. Plane-parallel, subangular greenstone. Both parallel surfaces marked by strong grooves, half-length or over, and sub-parallel in at least four systems. Edges broken; a few delicate striations.

No. 16, 16 by 8 by 4 cm. Irregular prism having one especially flat face parallel to structure marked by subparallel moulding striations. A few scratches elsewhere.

No. 18, 9 by 8 by 4 cm. Triangular tabloid black slate with one crude parallel system on each of two faces, with some additional striations elsewhere.

No. 25, 10 by 5 by 4 cm. Smooth parallel prismoid with broken ends, black slate. Parallel moulding striations on all sides.

In the deposit as a whole, at least 75 per cent of all clearly striated pieces were black slate and 90 per cent of all slate is striated. Apparently only the slate is fine-grained enough to carry the marks of rather feeble shaping processes. Only a very few diorite blocks are either faceted or striated.

Series No. 5, 55 specimens (Location 44)

Kame gravels, Herbert Glacier.

Fifty-five cobbles were measured, three diameters and the radius of curvature of the sharpest edge or point. Fifty of these were taken at random and showed roundness ratios as follows: Over 0.50, 1; 0.50–0.40, 7; 0.40–0.30, 9; 0.30–0.20, 25; 0.20–0.10, 8; under 0.10, 0; Average, 0.29.

The majority are spheroidal, nearly equidimensional cobbles. Only eight of the fifty had one dimension twice another, an unusually small proportion.

Five cobbles were selected as the roundest to be found and had roundness ratios of 0.41, 0.44, 0.52, 0.56, and 0.68.[2]

Series No. 6, 25 specimens (Location 72)

Roadside outcrop of glacial till several miles seaward from present terminus of Mendenhall Glacier.

Sizes ranged from 4 to 20 cm. The majority were subangular, showing some broken surfaces; only three were classed as subrounded. A variety of slaty, schistose and siliceous rocks were present. Only three showed sharply-cut, plane facets with sharp edges. All were marked by short irregular scratches in the general surface. Six showed well-marked general striation parallel, or subparallel to length of cobble. These specimens represent a selected 1 per cent of all fragments exposed in 1,000 square feet. They are at least superior

[2] The roundness ratio is the quotient r_1/R, where r_1 is the radius of curvature of the sharpest edge and R is the mean radius of the cobble. It is equal to 1.00 for a sphere (3).

in definiteness of striation and faceting to those found at any point near the glacier.

Series No. 7, 20 specimens (Location 75)

From grooved surface of overridden and now re-exposed moraine along western front of Mendenhall Glacier.

Area 20 by 30 feet, specimens measured represent one-half of those striated and about 1 per cent or 2 per cent of all exposed cobbles of this size. Sizes ranged from 3 to 20 cm., nearly all are elongate prisms or slabs, with maximum diameters 2 to 10 times the minimum. The dominant striation pattern was subparallel moulded, with an incidence of 8.5 in the 20 specimens. There were four with parallel patterns, and 2.5 each of subparallel, scatter and grid patterns. About one-third are clearly snubbed on one or both ends. As a whole they are subangular, with a few subrounded in form. The following are fairly typical:

No. 2, 11 by 7 by 5 cm. Greenstone, smooth, subangular, one end snubbed, moulding striae and grooves.

No. 10, 13 by 6 by 5 cm. Triangular prismoid, parallel moulding striae, old snubbing, edges rounded.

No. 13, 18 by 18 by 7 cm. Rough, weathered greywacke. One facet and one irregular back surface, both crudely mould-striated.

This series showed more distinctive glacial shapes and marking than any other seen in Alaska.

The shape characteristics noted in the foregoing series, representing a total of 503 specimens, are listed below:

With the exception of the kame gravels (Series No. 5), the prevailing shapes are either elongate prisms or slabs as in Series No. 7 and No. 4, or angular and subangular as in Series No. 1, 2, 3, and 6. The slates, greenstones and like rocks tended to be in the form of joint-bounded prism and slabs, in part somewhat well smoothed and striated.

Well-marked facets due to glacial abrasion rather than to jointing were comparatively few. The most faceted series was No. 2, in which seven cobbles of a total of twenty-five, picked as 5 per cent of whole were noted as having facets. This amounts to a rate of 14 per 1,000.[3] Series No. 6 showed a rate of faceting of 1 per 1,000, while others ranged between these. Parallel to subparallel striations were abundant in certain series, reaching rates per 1,000 as follows, No. 1, 0; 2, 8; 4, 10; 6, 2; 7, 20; average, 10. Snubbing is mentioned in Series No. 4 and No. 7, with a rate per 1,000 in No. 7 of 7. Short or crude irregular scratches are present in rates of 10, 10, 28, 30, and 50 for 1,000, in five of the series. Very few grid patterns were seen. Rates of 1 and 4 per 1,000 were noted.

Summary of Shape Characteristics.—It is necessary to distinguish in principle between several categories of glacial cobbles, even though in the field they are much mingled and often indistinguishable. Much completely angular debris, from blocks many tons in weight to sand grain sizes, is carried on the ice of some valley glaciers and deposited at the terminus without modification.

Some rock fragments are carried at and near the bottom of the glacier and suffer more or less faceting, striation, chatter-marking, and snubbing. The variety and completeness of the characters produced in this way depend much on the lithology of the

[3] These rates are all referred to the entire deposit by use of the estimated percentages of relation between the deposit and the picked series.

rock. Slate, more than any other crystalline rock, is commonly not only minutely and delicately striated and otherwise marked, but is also less subject to subsequent chemical attack on the surface and furnishes the most perfect specimens. Its cleavage into slabby and elongate fragments probably also favors the production of characteristically parallel striated and snubbed specimens which appeal to the geologist as distinctive. Granite, diorite and other coarse-grained rocks do not take the more minute markings and show much less distinctive effect of glacial abrasion even under similar conditions.

Many morainal accumulations are formed of partially waterborne debris and the high degree of rounding of the pebbles in certain kame gravels and parts of some of the moraines is very striking. With these confusing types and varying degrees of development of glacial shapes and markings in mind, the writer has attempted below to describe both the ideal features found under special conditions and the usual composition of an assemblage of glacially-handled fragments.

The general conception of the shape and markings of glacial cobbles held by most geologists has been based on the cobbles found in the deposits of continental glaciers in North America and Europe. Emphasis has been placed on forms which are in reality ideal, but are unfortunately described as typical. Beyond recognizing the distinction, it is possible that no satisfactory description of the typical glacially-placed cobble can be formulated. Such an entity is essentially only a statistical value, a mean of all the unmodified and partially modified glacial fragments with the few mature and nearly ideal forms found sparingly in most glacial drifts.

The most elementary products of glacial action are the single or few scattered scratches on otherwise unmodified surfaces. With repeated abrasion of slight intensity the surface of a rock fragment may be irregularly and generally scratched without the production of systematic striation patterns. With more sustained and intense abrasion the surface tends to be more systematically striated and more or less well-defined facets are cut. Such features as chattermarks and snubbing are also due to the more intense action of ice under higher bearing pressures which momentarily and locally reach the rupturing strength of the rock through the application of the ice pressure on a large area to a much smaller area of rock.

The most striking specimens are produced when rocks soft enough to be efficiently carved and smoothed by debris-laden ice are so faceted and smoothed, and at the same time or subsequently are sharply and cleanly graven by a few hard points or rock particles. The accidents of shifting from one position to another account for these occasional specimens which show numerous sharply marked plane facets, with multiple striation patterns on them.

The essential element in a characterization of maturely shaped glacial

cobbles, is what may be called the stoss-snub surface, a surface of which the front or push end is slightly rounded with a smooth transition to the slightly curved, or plane, main surface, and of which the other end is marked by breaking away through snubbing. The analogy with the form of roches moutonnées or any strongly glaciated rock surfaces is apparent. Having this element in mind the following seem to be the essential features of valley glacier cobbles and boulders.

(a) They have general proportions and texture of surface determined by the fracturing of the parent rock.

(b) They are modified by having impressed on them one or several form elements, each of which consists of a flat or slightly curved surface having one stoss end and one snub-fractured end. This surface may be called the stoss-snub surface. The various forms which glacial cobbles and boulders assume appear to be due to the development of one or more stoss-snub surfaces on shapes previously roughed out by the characteristic fracturing or jointing of the rock. If the stoss-snub surface is developed maturely on two broader sides of tabular parallelopipeds of such rock as limestone, we often have the pentagonal form so marked in the series of glacial cobbles studied in Wisconsin (6), and the flat iron shape of Von Engeln (2). On the other hand, with many varieties of rock, such as granite, diorite, basalt, and the like, the carving of a few random-oriented stoss-snub surfaces apparently produces few, if any, pentagonal or flatiron shapes. Intermediate between these are the shapes developed on elongate prismoids such as jointed greenstone, schist, or slate, on which the stoss-snub surface may appear on any or all of the four long faces, and with similar or reversed orientation.

(c) Most commonly the stoss-snub surface shows few if any cross-striations. Subordinately, on surfaces that are nearly equidimensional, cross-patterns become developed by turning of the cobble to new orientations. The typical grid pattern appears where two or more sets of differently oriented striations are lightly developed on a nearly plane surface.

(d) The rounding of edges of the stoss-snub surfaces is due to the combined stoss abrasion at the frontal edge, the subsequent rounding of snub-fractured lee edges, and the general accidental rounding sustained both during movement in and under the ice and in the course of placement in the terminal drift. Such smoothing of the general surface, as distinct from the stoss-snub surfaces, as takes place is due to this general accidental rubbing and battering.

(e) Glacial cobbles fall into three general end-categories and various intermediate positions. These are (1) Angular, rough, initial shapes due to the fracture characteristics of the rock and the disrupting process; (2) maturely faceted and striated cobbles, (3) rounded, water-worn shapes developed in super- and sub-glacial streams and in the glacial outwash channels. All three types and many intermediate forms are represented

in most morainal accumulations, the proportions depending on the remoter and more immediate controlling conditions. It is evident that coarser valley glacier detritus and that of a continental glacier and the various phases of each differ from one another in the proportions of these three extremes and the distribution of intermediates. Thus it appears, though the writer in Hawaii is scarcely in a position to test it, that a useful scheme of analysis might be based on a triangular diagram with these three extremes at the points. A random collection of fragments of a given drift, of all sizes, or of particular sizes, could be inspected and assigned various positions on the diagram, according to their estimated possession of various characteristics. A mass diagram could be built up in this way which might be a very useful characterization of the shapes of debris fragments of a given drift, or local deposit.

THE SHAPES OF ICE-JAM COBBLES

Detailed Observations.—Cobbles and boulders marked and shaped by ice-jam action were studied at various points between Dawson and Circle on the Yukon River. The following series were subjected to specific measurement and analysis.

Series No. 8, 10 specimens (Location 182)

From river bank about 10 miles downstream from Dawson.

No. 1, 15 by 13 by 8 cm. Subangular tetrahedron, all surfaces nearly plane. Faint striae on all, pronounced on two Mostly subparallel, single or paired. Lengths one-twentieth to one-half of facet length, many somewhat curved.

No. 2, 27 by 21 by 12 cm. Subangular fraction of former lenticular quartzite. Both broad sides generally striated, one strong parallel system, various other single or paired striae, mostly parallel but some transverse.

No. 3, 28 by 18 by 11 cm. Subangular, half remnant of former lens. Broad side shows nearly random criss-cross pattern, single pairs, small systems. Short compound bruises, and the like. Other side similar but less well developed.

No. 4, 10 by 9 by 7 cm. Subangular, irregular quartzite. Several small, paired bruises.

No. 5, 22 by 15 by 12 cm. Subangular, reentrant, one nearly flat face shows nearly random short scratches, singles and pairs, some curved. Other sides show bruises.

No. 6, 18 by 13 by 9 cm. Subangular tabloid. Singles, pairs and systems, both parallel and transverse, some curved, one flat surface.

No. 7, 30 by 20 by 14 cm. Subangular chipped river cobble, one compound flattish surface random short, singles and doubles, some curved. Generally one flat surface.

No. 8, 20 by 15 by 12 cm. Subangular half of subrounded lens. Fair system, both transverse and longitudinal, one side, singles and doubles, some curved other side.

No. 9, 15 by 12 by 5 cm. Subangular fraction on former lens. Few delicate gravings on harder parts of surface, also few small random bruises.

No. 10, 14 by 11 by 8 cm. Subangular to subrounded smooth cobble with few small short scratches and few curved diagonal edge bruises.

Series No. 9, 50 specimens (Location 204)

River bank at Eagle, Alaska.

This series consisted of all cobbles exceeding 15 cm. diameters found along the bank at this place. The largest were about 40 cm. in diameter. Most were rather compact; 22 had a maximum diameter less than twice the minimum and only 7 exceeded the ratio 3 in this respect. Twelve were described as subrounded, 30 were subangular and 8 were subangular and 8 were angular, sharp-edged or rough. Seven carried parallel, deep striae on some part of the surface and an equal

number showed parallel bruising but less clean scratching. Twenty of the 50 showed no striae at all. The remaining 16 were marked by random scratches, mostly scattered. Of those with parallel markings three showed two-fold grid systems of striae and three showed three-fold grid systems. Eleven showed strongly striated surfaces with extent exceeding one-half the whole surface area.

Series No. 10, 10 specimens (Location 207)

River bank near Eagle, Alaska.

Selected striated cobbles from are a 100 feet by 15 feet, of which 15 per cent was exposed.

No. 1, 20 by 15 by 9 cm. Subangular half of subrounded boulder, smooth surface generally striated, extent 0.9. Several small, parallel, deep striae, numerous random striae, some two-fold grid, few large parallel bruises, some chatter marks, spacing medium to close.

No. 2, 25 by 16 by 13 cm. Subangular smooth surface, generally scratches, extent 0.95, considerable parallel, deep striation on larger surfaces, some subparallel striae, many random striae, a few three-fold grids, spacing rather close.

No. 3, 17 by 14 by 11 cm. Subangular, smooth surface, generally scratched, extent 0.8, a few parallel, deep striae, mostly random striae, some parallel bruises.

No. 4, 18 by 14 by 13 cm. Subangular, joint-bounded, one surface striate, extent one-third, long parallel, deep striae, plus long three-fold grid, other surface a few random striae, spacing medium.

No. 5, 26 by 18 by 12 cm. Angular fragment of previous subangular boulder. Principal surface (extent 0.4), closely striated, a few long parallel, deep striae, generally long three-fold grids, a few parallel bruises and chatter marks. Other surfaces a few random striae.

No. 6, 18 by 13 by 7 cm. Subangular smooth, one surface striate, extent one-third, a few long parallel bruises.

No. 7, 12 by 10 by 14 cm. Subrounded lens, smooth, one side several long crude parallel bruises.

No. 8, 15 by 10 by 8 cm. Subangular smooth surface, striated extent 0.7. Minute parallel, deep striae plus random striae, medium spacing.

No. 9, 18 by 13 by 9 cm. Subangular, smooth, one flat joint surface, nearly complete system parallel bruises, otherwise not striated.

No. 10, 31 by 23 by 9 cm. Subangular tabloid. Both large surfaces striate, extent 0.8. Both show pronounced parallel, deep striae plus subparallel striae plus three-fold grids, spacing medium to close. Few random striae, remainder of surface.

Series No. 11, 25 specimens (Location 208)

River bank, near Eagle, Alaska.

These are all cobbles over 15 cm. in diameter in a certain area. Shapes are compact to moderately elongate. Only two are subrounded, twenty are subangular and three are rough and angular. Fourteen showed no scratches, eight showed only scattered random striae. The remaining three showed fairly general scratching over much of the surface, one a two-fold grid and another a three-fold grid.

Series No. 12, 10 specimens (Location 209)

Near Eagle, Alaska.

Ten boulders 30 cm. or over.

No. 1, 28 by 17 by 14 cm. Subangular to subrounded end of former ellipsoid. Surface completely striated. One flat surface carries parallel, deep striae, plus three-fold grid, very close. Remainder shows parallel, deep striae plus subparallel striae plus numerous random striae, close.

No. 2, 25 by 16 by 12 cm. Subangular, medium smooth, no striae.

No. 3, 24 by 13 by 10 cm. Subparallel smooth, extent 0.9, faint parallel scratches, also parallel bruises, plus scattered random striae, medium spacing.

No. 4, 24 by 21 by 13. Angular end spall from previous subangular block. Smooth surface, striated, extent 0.9, parallel, deep striae plus three-fold grid, spacing medium.

No. 5, 22 by 14 by 10 cm. Subrounded ellipsoid, smooth, a few random striae.

No. 6, 22 by 16 by 11 cm. Subangular, smooth surface, striated, extent 0.8, mostly random striae, medium spacing.

No. 7, 28 by 21 by 12 cm. Subrounded surface, rough, weathered, with a few coarse bruises.

No. 8, 22 by 16 by 11 cm. Subangular, smooth surface, extent 0.1, mostly random striae, plus parallel bruises.

No. 9, 23 by 14 by 12 cm. Subangular, irregular, with reëntrants, random striae, extent 0.33.

No. 10, 44 by 20 by 15 cm. Subangular rough block, no scratches.

Of 115 cobbles and boulders specifically noted, 11 were angular, 88 subangular and 16 subrounded.

Among 30 cobbles and boulders so discriminated, 9 were described as subangular and smooth, 8 as subangular fractions of former rounded or lenticular river shapes and 5 as subangular and irregular or rough. Only 3 were called joint-bounded or tabloid. No well-marked facets due clearly to ice abrasion were seen. In two random series of 50 and 25 specimens each, 20 and 14 specimens respectively (Series No. 9 and 11) showed no striae whatever.

Of 70 specimens showing any sort of striations, 23 carried some parallel striations, 17 carried grid patterns, 22 carried scatter of random patterns and 21 were marked by crude bruises, with considerable overlap and doubling of these features on certain specimens. Curved striations were specifically noted on 5 specimens, but also occurred on others.

Of 20 specimens so discriminated, 9 were scratched or striated on more than 80 per cent of their surface.

SUMMARY OF SHAPE CHARACTERISTICS

(a) River-ice-shaped cobbles have almost exclusively subangular to well-rounded, stream-abraded forms, only slightly modified by the ice action. The form doubtless differs somewhat according to the stream involved and the rock of which the fragments are formed, but with most of the rocks found in the Yukon Valley, the cobbles were compact and fairly well smoothed.

(b) The cobbles rarely if ever have broad, or plane facets definitely cut by ice action.

(c) Strongly parallel striation patterns moulded over a doubly convex surface are common.

(d) The most usual pattern consists of irregular, random, short striae or irregular bruisings. Widely spaced, two-fold, or three-fold grid patterns of striations are also fairly common on ice-jam cobbles.

(e) Snubbed ends and edges are comparatively rare. Crude chattermarks are occasionally found on ice-jam cobbles.

(f) Parallelism between the striation pattern and the long axis of the cobble is not especially evident.

(g) Short, crude, simple or compound bruises are common on ice-jam cobbles.

(h) Carved scratches or bruises are fairly common.

COMPARISON AND GENERAL SUMMARY

There is no absolute difference between the striating and faceting action of glacial ice and that of river ice in ice-jams. Certain differences in degree have been enumerated in a previous paper (5, pp. 75–80). The chief differences lie in the greater

areas over which strong pressure can be applied by glacier ice, the greater continuity and fixity of direction of motion of glacier ice at a given point, and the far greater total capacity for abrading and striating work by glacier ice. Because of the essential similarity of the action of glacial and ice-jam ice, there appear to be no characteristics of shape or striation which are unique in one or the other type of cobble. We are, therefore, obliged, in attempting to discriminate the two types, to rely on relative abundance and perfection of various characteristics. As a result of the foregoing extended observations and measurements, the following dicta are believed to hold.

(1) Initial shapes of either glacial or ice-jam cobbles are those due to fracturing or jointing of the parent rock. Maturely developed glacial cobbles take on shapes marked by one or more stoss-snub surfaces and with favorable rock types may show a significant proportion of pentagonal or flatiron shapes. The most maturely developed ice-jam cobbles do not show distinctive ice-controlled forms but remain, with possible rare, individual exceptions, river-smoothed and rounded cobbles.

(2) Facets, or stoss-snub surfaces, do not occur on the majority of cobbles in most glacial drifts, but are found rather generally on selected series of glacial cobbles. On ice-jam cobbles, even in selected series, they occur very rarely, if at all, in acceptable distinctness.

(3) Selected cobbles of either variety may show surfaces which are 80 to 100 per cent marked by striations. It is impossible to compare the relative abundance and degree of striation without regard to type, because of the difficulties in defining degree of selection and limits of deposits.

(4) Strictly parallel systems of striations on plane, cut facets are rare on glacial cobbles and do not occur on ice-jam cobbles. Subparallel patterns are fairly abundant on both glacial and ice-jam cobbles. On the glacial cobbles they may occur both on plane facets and in moulded configuration on curved or doubly curved surfaces. On ice-jam cobbles they occur only in the latter form, as a nearly parallel brushing over and around the pre-developed shape of a river cobble.

(5) Random, scatter patterns of short, single striae or small groups, are common on both types but are more distinctive of ice-jam cobbles because of the lack of facets on the latter and because the larger part of the surface is not commonly marked by more mature patterns.

(6) Grid patterns, especially widely-spaced, are much more abundant, relatively, on ice-jam than on glacial cobbles.

(7) Crude, broad, short bruises are quite characteristic of ice-jam cobbles and occur on a negligible proportion of glacial cobbles. This appears to be one of the most distinctive differences.

(8) Curved striae, especially of a crude variety and merging with bruises and gouges, are also quite common on ice-jam cobbles and com-

paratively rare on glacial cobbles, another rather clear difference.

THE ORIGIN OF STRIATED COBBLES OF SOUTHERN STATES

Unfortunately, it has not been practicable for the writer to re-examine the striated cobbles of various river terraces in the southeastern states, earlier study of which led up to the Alaska-Yukon study. It is probable that with the more definite criteria formulated a more detailed listing of evidence could be made. It appears, however, on the basis of previous extensive attention given these cobbles, that they have far more of the characteristics of ice-jam cobbles than of glacial cobbles. This conclusion is supported by inspection of illustrations in several of the writer's previous papers, including photographs of striated cobbles in an unpublished thesis on terrace gravels, and filed photographs of striated cobbles from terrace deposits.

In the summarized description of the cobbles of terraces in southeastern rivers previously published (4) the following statements are made: (1) Shapes do not differ greatly from those in modern streams; (2) a few true facets are found, but these are not abundant; (3) the majority have shapes of subangular to subrounded stream cobbles; (4) the majority of cobbles have striation patterns transitional between the grid pattern and the scatter pattern; (5) some very fine grid patterns occur.

These characteristics, together with the facts of their distribution in river terraces, strongly support the view that the striated cobbles of various southeastern river terraces are the result of ice-jam action.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 6, NO. 2, PP. 109–118, FIGS. 1, TABLES 1–4, AUGUST, 1936

THE SEDIMENTS OF THE PEARL AND HERMES REEF

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ABSTRACT

A detailed study of some bottom samples collected by P. S. Galtsoff during a survey of the Pearl and Hermes reef in 1930 has yielded some interesting quantitative data on modern tropical reefs. About half of the bottom material is composed of coralline algae remains; 17.8 per cent of mollusk shells; 16.6 per cent of coral fragments; and 6.3 per cent of foraminifera tests. The remaining 10.8 per cent is classified under eight other groups of constituents. The mechanical analyses reveal a symmetrical gradation of particle size ranging from coarse gravel near the inner edge of the reef to fine sand near the center of the lagoon. Comparisons of some organic ratios are made with shallow water marine deposits of southeastern Florida and the Bahamas.

Pearl and Hermes Reef, an atoll lying near the western end of the Hawaiian Archipelago, is about 1,100 miles from Honolulu. Its position, as determined by Lieut. M. M. Nelson, U. S. N., in 1930, shows it to lie between latitudes 27° 44′ 30″ N to 27° 58′ 00″ N and longitudes 175° 42′ W to 175° 59′ W. The atoll is roughly elliptical in outline, its length being 17 nautical miles and its width 10 nautical miles. Its circumference is about 43 nautical miles, with the long axis trending in a northeasterly direction.

According to Galtsoff (1), the rim is formed largely by coral reef. It is about 250 feet wide and extends around about two-thirds the circumference of the lagoon. The northwestern side is open to the Pacific Ocean. Depths inside the lagoon range from 1 to 104 feet (about 0.3–31.0 meters). The reefs within the lagoon have shallow central areas surrounded by rims of coral. These reefs within the main atoll rim are much smaller features than the *faro* and *velu* described by Gardiner (2). These central portions vary in depth from 1 to 2.6 meters and are usually covered by a thick layer of soft sand. The outer slopes of the atoll rim extend steeply to depths of around 20 meters at which depth the fine-grained mud of the ocean floor begins. Galtsoff further states that the entire lagoon can be divided roughly into two sections. The central and northern parts of it are occupied by coral reefs, while sandy bottoms extend along the eastern and southern portions.

The atoll is situated at the northern edge of the Northeast Trades, where for most of the year the prevailing winds are from the northeast, but for the months of December to February, inclusive, the direction of the wind is very variable. As regards marine currents, the atoll is situated near the northern margin of the North Equatorial drift, where for most of the year the drift is from the

southeast. The direction of the surface drift conforms to the principles of Ekman's theory of wind-induced currents in an open ocean; that is, approximately at right angles to the right of the direction of the prevailing winds. The atoll rim in its plan conforms to the system of prevailing winds and surface currents. The northeastern arc of the rim is bowed toward the direction from which the winds blow; while the southern segment of the rim conforms to the direction of the surface marine currents (see monthly Pilot Charts of *U. S. Hydrographic Office*).

A survey of the conditions of the pearl oyster beds of this area was conducted by the United States Bureau of Fisheries in 1930. The expedition, in charge of Dr. P. S. Galtsoff, obtained many data on bottom configuration, biological conditions, water temperatures, salinities, and bottom deposits. Part of the bottom samples were sent to the Scripps Institution by Galtsoff in 1931. Recently the material was placed by Dr. T. W. Vaughan at the disposal of the author for study. A select group of twenty samples was taken from the collection and an-

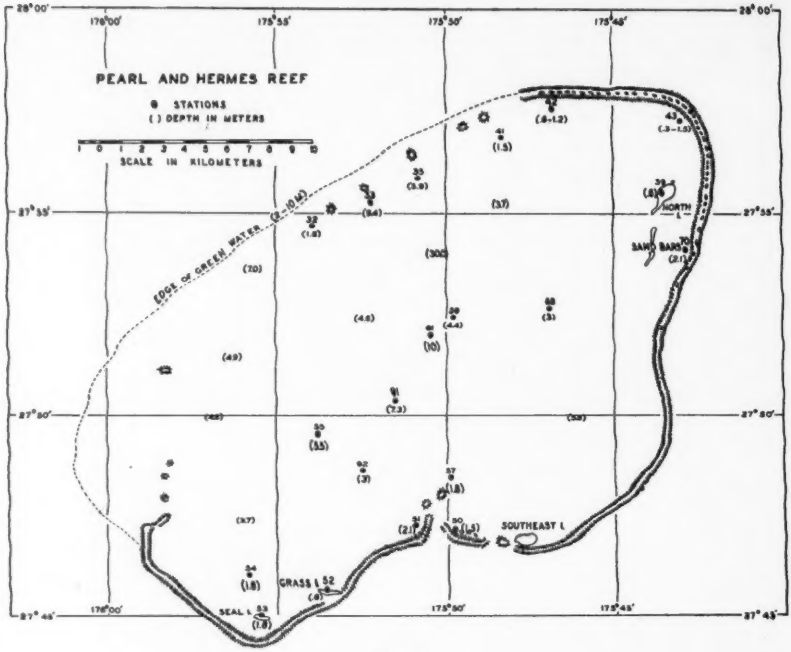

FIG. 1

alyzed mechanically. Portions of the separated fractions were then subjected to microscopic analysis and rough quantitative count. The method of estimating proportions of constituents has been used on other occasions by the author (4, 5), and in practice has served very well for the purpose.

MICROSCOPIC ANALYSES

Calcareous algae.—From a quantitative basis calcareous algae furnish about half of all the calcareous material contained in the lagoonal sediments. Here, as in many other tropical reefs, the calcareous algae are the principal reef builders. Corallinaceae exceed *Halimeda* in amount in 15 samples, about equal it in one, and are exceeded by it in 4 cases (Nos. 32, 33, 61, and 91). Algal remains are resistant to wave action, hence preserve their structure even in the smallest sand grains.

Mollusks.—Second in importance to calcareous algae are the mollusks. Both gastropods and pelecypods are common. Some species exhibit brightly colored shells of red, pink, or salmon hues, and a few pelecypods have heavy, massive shells. The relative durability of mollusk remains permits the accumulation of their shells over a considerable period of time, hence the population at any given time may not be ascertainable from the shells found. Galtsoff records the following common species: *Pinctada galtsoffi* Bartsch, to study which was the purpose of expedition, *Conus litteratus* var. *millepunctatus* Lamarck, *Conus ebraeus* Linneaus, *Terebra maculata* Linnaeus, *Spondylus tenebrosus* Reeve, *Arca ventricosa* Lamarck, *Pedalion costellatum* Conrad, and *Tonna melanostoma* Jay.

Madreporarian corals.—Some of the bottom samples contained the highest proportion of coral ever examined by the author. Seven samples contained over 20 per cent, the maximum being 29.8 per cent. The mean value for all twenty samples was 16.6 per cent. It should be noted that coral skeletons break down very easily under the action of waves and, as a result, the small sand grains of coral are very difficult to identify. Of the major constituents considered, coral is the one most likely to be improperly identified. The most important genera represented are *Porites*, *Pocillopora*, *Montipora*, and *Dendrophyllia*.

Foraminifera.—Protozoan remains are well represented by foraminiferal tests. The large *Marginopora* and *Amphistegina* are well distributed, as are also *Peneroplis* and *Sorites*. Large specimens of *Heterostegina* and *Miniacina* are found occasionally. *Quinqueloculina*, while present, was not encountered in any great numbers. This is contrary to the findings in many other tropical reef localities. Monstrous forms are not uncommon, especially in the genus *Peneroplis*, where several double-apertured specimens were observed. New growths, representing repair of broken tests, were seen in specimens of *Sorites* and *Marginopora*. Two specimens of *Globigerina* were found in sample No. 53. Since neither radiolarian nor pteropod remains were found, it

TABLE 1.—*Microscopic Analyses. Constituents of the Samples*

Sample Nos.	32	33	35	39	41	42	43	50	51	52	53	54	55	57	59	61	68	70	91	92
Algae, calcareous	44.7	66.6	66.4	38.7	71.0	53.7	56.9	48.5	54.0	56.4	50.8	44.4	38.5	46.7	28.6	35.5	49.1	34.0	55.4	30.5
Bryozoa		0.3		0.2		0.2		tr	tr						tr	tr		0.2	0.1	
Coral, Madreporarian	29.8	3.9	6.3	25.2	7.3	22.0	13.7	17.8	13.3	14.4	13.9	27.5	22.3	18.0	19.3	11.3	20.1	26.9	8.9	9.5
Crustacea	0.3	0.6		0.2	tr	0.2	1.0		0.9	0.2	0.3	0.1	0.3	0.3	0.1	1.5	0.5	0.2		0.1
Echinoidea	1.7	2.0	1.9	0.8	1.0	0.3	1.1	2.8	1.7	2.3	1.8	0.8	1.1	0.1	0.1	0.3	0.3	1.3	0.2	0.5
Fish teeth					tr	tr														
Foraminifera	3.5	2.8	3.5	13.5	6.0	8.0	7.7	9.6	9.3	8.6	10.8	2.4	6.4	4.4	2.5	1.6	4.6	6.2	5.3	9.3
Mollusca	16.4	13.7	13.1	10.6	10.7	8.6	14.3	16.4	18.6	13.9	9.3	7.9	22.8	22.0	32.7	29.9	17.1	20.2	14.3	42.9
Spicules, spines	1.1	1.0	0.3	1.3	0.2	0.9	0.5	0.4	0.2	0.5	0.4	0.2	0.3		0.4	0.4	0.4	0.2	0.1	0.1
Worm tubes	0.7	0.6	0.1	0.2	0.1	0.3	0.4	tr	0.2	tr	0.5			0.4	0.3	0.3	0.3	0.4	0.4	0.3
Limestone and unclassified $CaCO_3$				2.9							2.9				3.3	1.6		8.5		2.3
Minerals, noncalcareous	tr			0.2	tr	2.3	tr	0.3	tr	tr	2.1	6.6	2.7	tr				tr	tr	tr
Silt and clay	1.9	8.6	8.9	6.2	3.8	3.4	4.4	4.2	1.8	3.6	7.3	9.8	5.5	7.6	12.7	18.0	7.3	1.9	15.4	4.7
Total	100.1	100.1	100.5	100.0	100.1	99.9	100.0	100.0	100.0	99.9	100.1	99.5	99.9	99.5	100.0	100.6	99.7	100.0	100.1	100.2

appears that the outer reef is an effective barrier to the entrance of most open-sea pelagic organisms (Table 2).

Echinoidea.—Sea-urchin spines are common constituents of the lagoon sediments. The characteristic colors and ornamentation on the spines made it possible to identify *Heterocentrotus* (reddish, purplish), *Echinometra* (black), and *Brissus* (gray, brown).

Spicules, spines.—Triaxial and monaxial sponge spicules are relatively common. Holothurian spicules are found in the silt and clay portions of most samples.

Crustacea.—The lobster *Panulirus* contributes remains to the sediments, as do several unidentified crabs and some ostracods. While quantitatively unimportant, crustacean fragments having a diameter of 0.05 mm. can be recognized easily.

Worm Tubes.—As a rule, worm remains are relatively scarce but it is seldom that one fails to find at least one or two fragments of worm tube in a sample.

Bryozoa.—Only a few fragments were seen.

Limestone and unclassified $CaCO_3$.—A small per cent of the organic skeletons could not be identified. Usually there were no diagnostic external characteristics preserved and the amount of information to be gained by further study was small in

TABLE 2.—*Distribution of Foraminifera*
(A = abundant; X = more than one specimen seen but not abundant)

Species[a]	Sample Nos.																		
	32	33	35	39	41	42	43	50	51	52	53	54	55	57	59	61	68	70	91	92
Amphistegina	A	A	A	A	A	A	A	A	A	A	A	X	A	A				A		A
Bolivina												X						X		X
Borelis	X																			
Discorbis									X				X	X			X	X	X	X
Epistomina								X			X									X
Eponides				X	X						X									
Globigerina											X									
Gyroidina					X															
Heterostegina	X		X			X	X		X	X	X							X		
Lagena												X		X						
Marginopora	A	X	A	A	A	A	A	A	A	A	A	X	A	A	X	X	A	A	A	A
Nonion																X	A			
Peneroplis				A	A	A	A				X	X								X
Planorbulina				X							X				X	X	X	X	X	
Polytrema																				
(Miniacina)					X	X	X			A	X	X						X		
Quinqueloculina				X		X			X						X	X	X		X	
Reussella						X														
Sorites	X	X	X	A	X		X	X	X	X	X?	X		X	X	X	X		X	X
Spirillina				X						X	X									
Spiroloculina				X											X	X			X	X

[a] *Anomalina, Articulina(?), Asterigerina, Cibicides, Rotalia* found occasionally but not in sufficient numbers for enumeration.

proportion to the time required to classify them. In addition to these grains one occasionally found pieces of limestone. These indurated rock fragments are especially interesting because they were probably derived from calcareous reef material which had been exposed to the atmosphere either by elevation of the reef or by depression of sea level. Galtsoff mentions the occurrence of isolated limestone rocks within the lagoon which project about 1.5 meters above sea level. These so-called "horses" which occur here in the northeastern part of the lagoon have been reported from many atolls of the Pacific and Indian Oceans (3).

Non-calcareous minerals.—A few volcanic rocks are intermingled with the calcareous sediments. No attempt was made to classify them except that they are quartz-bearing and the groundmass is intermediate to slightly basic. Traces of magnetite, mica, and volcanic glass were found in some samples. The larger volcanic fragments were obviously derived from below the reef and show that the reef structure rests on a volcanic basement. The glass and ash were probably brought in by waves and currents and perhaps some of it may be wind-blown.

Silt and clay.—The sizes of particles of these two fractions are too small for accurate estimation of all constituents. Among the things definitely recognized are calcite, foraminiferal tests, crustacean fragments, molluscan fragments, volcanic glass, quartz, and mica. No aragonite needles were seen.

A survey of the microscopic analyses shows that four groups of organisms dominate the sediments of the interior lagoon. In descending order of importance they are: calcareous algae, 48.5 per cent; mollusks, 17.8 per cent; madreporarian corals, 16.6 per cent; foraminifera, 6.3 per cent: total of all four, 89.2 per cent. The other organic groups and minerals, silt, and clay contribute only 10.8 per cent of the total. The ratio of calcareous algae to the second most abundant group, the mollusks, is 2.73; to the third ranking group, madreporarian corals, 2.93; and to the fourth, foraminifera, 7.7. These ratios, as well as the relationships of mollusks, corals, and foraminifera to each other, are represented in Table 3. Columns 2 and 3 of this table list, respectively, the relationships of the same four groups as estimated by the author for samples described from southeastern Florida and the Bahamas. By comparison, it is shown that there is nearly twice as much calcareous algae in the sediments of Pearl and Hermes reef as in southeastern Florida, and that there is more than two and a half times the quantity found in the Bahamian area. Mollusk remains are roughly of the same order of magnitude for Pearl and Hermes reef and southeastern Florida. A smaller proportion is indicated for the Bahamas. Considerably more coral occurs in the Hawaiian locality than either Florida or the Bahamas. Contrasted with this, the foraminifera of the Florida-Bahamian region contribute considerably more to their respective

sediments than do the foraminifera of Pearl and Hermes reef. There are several specific and generic differences between the two faunas. There is an absence of oolites, pellets, aragonite needles, and Alcyonarian spicules in the Hawaiian lagoon—constituents relatively widespread in southern Florida and the Bahamas.

Physico-chemical factors.—No chemical determinations were undertaken, but Galtsoff obtained temperature and salinity data over a 31-day period. His observations showed a gradual upward trend of water temperatures from about 25°C. in July to about 26.5°C. by the end of August. The extremes of temperature were 22.7° and 27.9°C. The bottom temperatures were only slightly less than the surface readings except for the deepest place, where a difference of 1.6° was found for a depth of about 30 meters. Salinity measurements showed a range of 35.6 to 36.6 parts per thousand with the average reading close to 36 parts per thousand. No particular trend was observed, although Galtsoff stated that his isohalines were drawn on observations made within a 31-day period and, therefore, only roughly represented the distribution of salinities in the lagoon. Apparently ocean water enters the lagoon principally through the southern boat channel and escapes through the open northwest side. The tidal range is about 2 feet and the tides apparently set north and south with an average velocity of 2 knots per hour.

While no analyses of sea water, except for salinity, are available, one might predict that since the salinity is not abnormally high, and because of the apparently easy access of ocean water to the lagoon, the water is not saturated to the point of precipitation with respect to calcium carbonate. Neither are the temperatures excessively high and there is reason to believe that they seldom exceed the maximum observed figure of 27.9°C because the observations were made, as stated previously, during July and August. No physical evidence of chemical precipitation, such as the presence of aragonite needles or oolites, could be found. It is believed that apparently all of the calcium carbonate in the sediments of the lagoon is derived from the skeletons of plants and animals.

TABLE III.—*Quantitative relationships of the four major constituents of samples from Pearl and Hermes Reef, southeastern Florida, and the Bahamas*

Constituents	Pearl and Hermes Reef (per cent)	Southeastern Florida (per cent)	Bahamas (per cent)
Algae, calcareous	48.5	25.1	18.0
Mollusk	17.8	17.5	12.2
Coral, madreporarian	16.6	9.3	8.2
Foraminifera	6.3	9.0	17.3
Total percentage	89.2	60.9	55.7
Constituent ratios			
Algae/coral	2.92	2.70	2.20
Algae/mollusk	2.72	1.43	1.47
Algae-foraminifera	7.70	2.80	1.04
Mollusk/foraminifera	2.82	1.94	0.71
Mollusk/coral	1.07	1.88	1.49
Coral/foraminifera	2.64	1.01	0.47

TABLE IV.—*Mechanical Analyses. Distribution according to size groups*

	Sample Nos.																			
	32	33	35	39	41	42	43	50	51	52	53	54	55	57	59	61	68	70	91	91
Size limits	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
64– 32 mm.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
32– 16 mm.	5.0	0.0	0.0	0.0	16.8	47.6	0.0	0.0	3.1	0.5	0.0	17.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16– 8 mm.	1.9	0.0	4.0	5.6	41.0	13.3	15.1	0.0	4.7	4.4	10.3	5.4	0.0	1.2	0.9	0.5	0.0	10.6	3.8	0.2
8– 4 mm.	2.6	10.7	5.5	4.7	13.0	4.0	4.2	1.4	4.2	3.7	5.7	4.9	0.0	0.8	0.8	2.5	0.0	10.7	3.0	0.1
4– 2 mm.	14.6	48.3	19.0	12.2	15.2	8.3	14.0	5.5	3.6	9.5	6.9	27.4	3.0	5.0	7.5	7.0	12.9	45.0	18.1	1.4
2– 1 mm.	6.7	14.2	31.3	7.2	4.4	3.2	4.6	7.1	6.2	11.7	8.6	29.9	33.0	18.4	6.9	7.5	6.0	4.1	12.3	13.6
1– .5 mm.	14.6	12.2	23.1	12.1	3.7	6.2	20.3	35.8	23.7	35.3	20.6	5.2	48.8	27.7	17.3	16.0	25.5	16.7	17.0	40.9
.5–.25 mm.	19.3	3.8	6.3	20.8	1.4	6.9	28.8	33.1	25.3	25.0	13.4	0.3	7.7	28.4	20.0	18.2	19.7	7.5	12.8	29.5
.25– .1 mm.	28.3	1.4	1.7	25.7	0.5	5.7	7.9	11.7	3.4	5.3	19.6	0.1	1.6	10.5	26.0	20.4	21.7	2.8	13.0	9.3
.1–.05 mm.	5.0	0.8	0.3	5.5	0.2	1.4	0.7	1.1	0.6	1.0	7.9	0.1	0.3	0.4	7.9	9.9	6.8	0.6	4.5	0.4
.05– 0 mm.	1.9	8.6	8.9	6.2	3.8	3.4	4.4	4.2	1.8	3.6	7.3	9.8	5.5	7.6	12.7	18.0	7.3	1.9	15.4	4.7
Total	99.9	100.0	100.1	100.0	100.0	100.0	100.0	99.9	100.0	100.0	100.4	100.1	99.9	100.0	100.0	100.0	99.9	99.9	99.9	100.1
Summary																				
Gravel, 64–2 mm.	24.1	59.0	28.5	22.5	86.0	73.2	33.3	6.9	39.0	18.1	22.9	54.7	3.0	7.0	9.2	10.0	12.9	66.3	24.9	1.7
Sand, 2–.05 mm.	73.9	32.4	62.7	71.3	10.2	23.4	62.3	88.8	59.2	78.3	70.1	35.6	91.4	85.4	78.1	72.0	79.7	31.7	59.6	93.7
Silt+clay, .05–0 mm.	1.9	8.6	8.9	6.2	3.8	3.4	4.4	4.2	1.8	3.6	7.3	9.8	5.5	7.6	12.7	18.0	7.3	1.9	15.4	4.7
Total	99.9	100.0	100.1	100.0	100.0	100.0	100.0	99.9	100.0	100.0	100.4	100.1	99.9	100.0	100.0	100.0	99.9	99.9	99.9	100.1

MECHANICAL ANALYSES

Table 4 shows the distribution of particles with respect to size groupings. Perhaps the most conspicuous feature of these sediments is the high proportion of sand and gravel. There are 15 sands, 5 gravels, and no silts and clays. Since deep water lies all around the lagoon and the prevailing winds are such that currents set towards the open west side of the reef, the deficiency of fine particles is easily explained by their removal into deeper water outside. The area containing the highest proportions of silt and clay lies in the center of the lagoon which is also the deepest part. Silt and clay combined total 18.0 per cent in No. 61. Other samples containing appreciable amounts of silt and clay are Nos. 91, 59, and 35, all from the deeper, central part of the lagoon. The lowest value for silt and clay is given for sample No. 51, 1.8 per cent. On the basis of mechanical analyses, it is estimated that about one-fourth of the area is covered by sediments containing more than 10 per cent and less than 20 per cent of silt and clay.

Surrounding this area of finer particles lie the coarser sand deposits. The highest values occur respectively in samples Nos. 92, 55, 50, 57, and 68. Sample No. 92 contains 93.7 per cent sand grains. About five-eighths of the lagoon is underlain by sand containing less than 10 per cent silt and clay and less than 50 per cent gravel.

The coarsest material lies on or very near the reef proper. This narrow belt of gravels, representing about one-eighth of the area, is separated from the central portion by the broad belt of sands. The greatest amount of gravel, 86.0 per cent, is found in samples No. 41. The other gravel samples are Nos. 42, 70, 73, 33, and 54.

SUMMARY

The sediments of Pearl and Hermes lagoon are predominantly calcareous sands and gravels. The isolated position of the reef precludes influx of material from a large land mass except for a small amount of volcanic dust and ash which may be wind-blown. The small area of reef exposed to the atmosphere limits the action of rain water in modifying the sediments. The rim of the lagoon is maintained by a coral framework reinforced by a vigorous growth of calcareous algae. While material is constantly being broken away from the rim it is still able to maintain an effective barrier against the ocean waves; in fact, it is believed that the latter have little effect on the sediments inside the lagoon. Because of the ineffectiveness of mechanical erosion the deposits tend to be very coarse. The smaller proportion of finer material is still further reduced by removal through current action to deep water outside the lagoon.

Ninety per cent of the material within the lagoon is composed of fragments of calcareous algae, mollusk shells, madreporarian coral exoskeletons, and foraminiferal tests. In comparison with sediments of southeastern Florida and the Bahamas, it was found that there is appreciably

more calcareous algae and madreporarian corals, about the same amount of mollusks, and considerably fewer foraminiferal remains in the Pearl and Hermes deposits. No Alcyonarian spicules, aragonite needles, oolites, or calcareous pellets were observed in the Pearl and Hermes reef sediments, although such constituents are relatively widespread in the Floridian-Bahamian area. It is thought that the temperature and salinity are not high enough to cause precipitation of calcium carbonate from the ocean water within the lagoon.

Evidence that at least parts of the reef have stood above the present sea level, or that the ocean stood at a higher level, is obtained from fragments of indurated limestone embedded in the sediments and thought to be derived from isolated limestone "horses" which stand about one meter above highest tide level. It is thought that Pearl and Hermes reef rests on a volcanic basement, because volcanic pebbles, presumably derived from below, are found in some of the samples.

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REVIEWS

NIELSEN, NIELS. *Eine Methode zur exakten Sedimentationsmessung.* Studien über die Marschbildung auf der Halbinsel Skalling, Biologiske Meddelelser, xii, 4, S. 1–98, Kgl. Danske Videnskabernes Selskab., Kobenhavn, 1935.

Skalling is a small peninsula which lies along the southern part of the North Sea coast of Denmark. On the inner side of the peninsula, sand plains give way to marshlands which border a small bay. Since 1930 a number of scientists have been attracted to the virgin territory, and have studied its flora, fauna, physiography, and other features in an intensive manner, both in the sand and marsh areas. Nielsen, one of the group, found that there was available but little information as to the causes of changes in shore lines and configuration of the peninsula, and still less about the evident movement of sand making up the plain and dune areas. To study this movement, he worked out an ingenious method:

To know where sand grains come from, and where they go, one must be able to recognize and differentiate individual grains. The easiest way of effecting this is to *color* the grains, so that they may be followed from place to place. Evidently, not many coloring agents will be satisfactory, since they must not change the surface and other characteristics of the grains, must be retained for the time of observation, and must be easily recognized in the field, i.e., must be brilliant or striking.

Nielsen describes five solutions which were used in early trials. Of these, only two were found to be practical: a/methylviolet in both water and alcohol solutions of from one-tenth of one per cent to 1 per cent; and, as finally used in most of the work, b/Sudan-red (Sudanrot), one-tenth of one per cent to 1 per cent solution in equal parts of benzine and benzol. Sudan-red is a fat-soluble aniline dye, which, in the solutions described, imparts to sand grains a bright, clear red color, which sinks into the grain without modifying the surface. It is not soluble in water. For use in regions of bare sand, a squirt gun is used to spread the dye solution over the surface, thereby imparting a characteristic color to the grains of a certain area. Movement of these grains can then be followed by finding them in other places.

The marshlands of Skalling offer another problem, which is the subject of the present publication. They show, from old maps, that they have changed and grown much in recent years, though the movement of sediment is not easy to detect, and one can not be sure that any given point is undergoing erosion or sedimentation at the time of observation. Obviously, the method of spraying color would not work in this type of surface, since the dye would probably be caught about the roots of plants, and would not penetrate a significant distance into the soil. To study the marshlands, a modification of the above method was necessary:

Sand previously treated with Sudan-red solution was sprinkled thinly (about 2 mm. thick) over the surface of the marsh. Then if sediment were deposited over it, later borings would show this fact, and the amount of new sediment could be immediately measured on the surface of a core.

Five areas, each about 10 by 10 meters, were covered in this way in 1931, and in 1932 they showed that the color was well preserved, and that a measurable thickness of sediment had accumulated during the year. In 1932 more elaborate "sprinklings" were carried out, so arranged as to traverse the parts of the marsh covered with different vegetation and lying at different elevations. Yearly measurements of the sprinkled areas up into 1935 showed the color in general well preserved and the areas recognizable (a few never found), and also a more or less equal annual increment of sediment.

The sediment is brought in and spread over most of the marsh during the time of spring floods, when the water reaches to about 30 to 40 cm. above the datum plane used in the work. Above that elevation sedimentation was found to be negligible, and below it, to vary in a general way with the elevation,—being heaviest in the lowest parts of the marsh. The annual increment is about 3 to 4 mm., and is very consistent withal. It varies with the type of vegetation (with limits from

0 to 10 mm.), in one part being mostly mud, in other parts, where the plant cover is less dense, it is mainly sand, and in the latter place it is more variable in thickness. All of the facts are brought out in simple curves and diagrams, and the different types of marsh and vegetation are shown in sixteen plates.

The author points out what is the most surprising thing to him: that there is taking place active sedimentation *on the land*, of the sort he had imagined to form only in the areas covered continuously by shallow water. But the process can proceed for only some 100 years with the present relations of land and water, since at the expiration of that time sediments will have excluded the spring flood from the part now covered every year. Thirty or forty cm. of sediment will represent the deposits of this time interval.

To the reviewer, it would be interesting to know the character of the sediments laid down in these annual tides. One might expect them to show some sort of bedding or banding, and they might have the nature of varves. On the other hand, since they are really bound together by the plants of their particular locality, growth and later decay of the plants may destroy all signs of bedding. Possibly not a few of our past sediments have accumulated in a similar way, and the information presented in this work should help in their interpretation.

Nielsen, in a later visit to England, found that something of the nature of his method had been used by F. J. Richards (*Annals of Botany*, 1934). Also, J. A. Steers (*Geol. Mag.*, vol. 72, pp. 443–445, 1935) gives a short account of his own recent work, and that of some others who had used essentially the same method as far back as about 1915. (Apparently most of the English work has been done with naturally colored sand.) However, credit should certainly be given Nielsen for working out the method himself, and for giving an excellent account of its use and importance. It should find, in addition to its past use in the determination of the rate of upbuilding of marshlands, a number of applications in the study of sediments.

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HJULSTRÖM FILIP, Studies of the morphological activity of rivers as illustrated by the River Fyris, *Geol. Inst. Upsala, Bull.*, vol. 25, pp. 221–527, 1935.

One of the most fruitful lines of attack in sedimentary petrology is unquestionably the study of current processes of erosion and sedimentation, with the view of discovering if possible the environmental factors and forces that control the entire series of events. Hjulström has approached the problem of the degradation of a river basin from such a point of view, and his publication deserves the critical attention of all workers in sedimentary petrology. The plan of the work is ambitious, and as the author himself states, "the paper may be considered to be a study of physio-geographical and geological dynamics. It has been written with the conviction that the knowledge of the forces at work on the land-surfaces of the earth is quite as important in geomorphology as the results brought about by these forces." Thus Hjulström shifts the emphasis from a study of land forms themselves to a study of the forces that operate to produce them. It is a point of view which impresses the reviewer as essentially sound, but it is open to the criticism from geologists of the conventional school, that in order to succeed one must become a physicist.

In developing his thesis, the author found it necessary to take excursions entirely outside the realm of conventional geology and to discuss such subjects as hydraulics in their connection with the nature of erosion, the laws governing the transport of sediment, and those which control deposition. Thus the book (for it runs 300 pages) begins with a chapter on the dynamics of streams, in which are defined laminar and turbulent motion. Vortices, eddies, transverse circulations—all the many complexities of movement are touched upon. Following this comes a chapter on solid matter in bed load and in suspension. Here again are critical examinations of the factors involved in moving material by fluid transport. Hydrodynamical upthrust, "exchange" (Austausch), and the like are discussed, and an attempt is made to determine the distribution of sand and silt in vertical section through the stream. Experiments bearing on these aspects of the case are described.

Chapter 3 treats at great length the subjects of erosion, transportation, and deposition. The relation between velocities and grain size is examined, and considerable space is devoted to erosion by cavitation. Modes of transport of material in streams, conditions of deposition, and stream capacities are among other topics discussed here.

These "preliminary considerations" occupy 125 pages of Hjulström's thesis, and Chapter 4 applies the point of view to the River Fyris. The extent of the basin, the types of rock present, climatological data, and the hydraulics (discharge, etc.) of the river are treated in detail. A section on the method of investigation then follows, which will be welcomed by workers whose interest lies in further applications of Hjulström's work. Finally, the River Fyris is examined in terms of the degradation of its basin, supported by a mass of quantitative data that cannot fail to be impressive. One of the outstanding features of the book is the detail with which the author examined the literature of his field, and the several hundred bibliographic items will make a valuable addition to the card catalogues of all workers interested in Hjulström's point of view.

The present review has been written not so much to present a summary of Hjulström's findings, but rather to induce sedimentary petrologists to read his paper for themselves. The work is in English, clearly written, and the author is to be complimented on the organization of his material and the logic with which he marshalls his evidence. Later work may or may not support every single thesis that the author advances, but the point remains that his work is dynamic and stimulating.

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BAAK, J. A., Regional petrology of the southern North Sea. *Geol. Lab., Agr., Univ., Wageningen*, Holland, pp. 1–128, 1936. English with a Dutch summary.

This work on the petrology of the southern North Sea presents the results of the studies in an introduction, six chapters and a bibliography. There is a map of the southern North Sea on which are shown the positions of the stations from which the samples were acquired. The first chapter presents the methods and principles of investigation of sedimentary petrology. Chapters 2 to 4 give in order the petrology of the sediments of the North Sea bottom, the Dutch coastal zone, and the French Coast on the North Sea. The minerals are described in Chapter 5 and in Chapter 6 there is treated the geology and geologic history of the North Sea bottom.

The studies of the southern North Sea sediments have made possible the division of the distribution of these sediments into five sedimentary—petrological provinces which are outlined in the text and illustrations (Fig. 8, p. 99). The character and distribution of the sediments aid in deciphering the geologic history of the North Sea.

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